APPLICATION OF PARTICLE SWARM OPTIMIZATION TECHNIQUE IN OPTIMAL LOCATION AND SIZING OF SVC

A DISSERTATION SUBMITTED IN THE PARTIAL FULFILLMENT FOR THE DEGREE OF

MASTER OF TECHNOLOGY
(POWER SYSTEM)
(2011 – 2013)

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CERTIFICATE

It is certified that **Mr. PRASHANT PANDEY**, Roll No 2K11/PSY/12, student of M.TECH., Power System, Department of Electrical Engineering, Delhi Technological University (Formerly Delhi College of Engineering), has submitted the dissertation entitled **"APPLICATION OF PARTICLE SWARM OPTIMIZATION TECHNIQUE IN OPTIMAL LOCATION AND SIZING OF SVC"** under my guidance towards partial fulfillment of the requirements for the award of the degree of Master of Engineering (Power System).

This dissertation is a bonafide record of project work carried out by him under my guidance and supervision. His work is found to be outstanding and has not been done earlier.

I wish him success in all his endeavors.

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JULY, 2013

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ACKNOWLEDGEMENT

The writing of this dissertation has been one of the most significant academic challenges I have ever had to face; without GOD's blessings and support, patience and guidance of the following people, this study would not have been completed. It is to them that I owe my deepest gratitude.

- **Prof. Narendra Kumar, Electrical Engineering Department, Delhi Technological University (Formerly Delhi College Of Engineering)** for their initiative in this field of research, for their valuable guidance, encouragement and affection for the successful completion of this work. Their sincere sympathies and kind attitude always encouraged me to carry out the present work firmly.
- **Prof. Madhusudan Singh,** HOD, Electrical Engineering Department, Delhi Technological University (Formerly Delhi College of Engineering), New Delhi, for providing me with the best facilities in the Department and timely suggestions.
- My Parents, who have always supported, encouraged and believed in me and patiently waited for my dreams come true.

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DECLARATION

I, hereby declare that the work being presented in this Project Report entitled **"APPLICATION OF PARTICLE SWARM OPTIMIZATION TECHNIQUE IN OPTIMAL LOCATION AND SIZING OF SVC"** is an original piece of work and an authentic report of our own work carried out during the period of 4^{th} Semester as a part of my major project. The data presented in this report was generated & collected from various sources during the above said period and is being utilized for the submission of my Major Project Report to complete the requirements of Master‘s Degree of Examination in Power System Engineering, as per Delhi Technological University curriculum.

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ABSTRACT

As economy grows, the demand of power increases. The increase in the reactive power demand may cause worsening in the voltage profile. To ensure the reliable power supply and to reduce the losses, reactive power compensation is required.

For reactive power compensation fact devices can be used. Here the Static Var Compensator (SVC) is taken as a case as shunt fact device. In this thesis, optimal placement and sizing of SVC considering the bus voltages and cost of installation has been formulated using stochastic approach. The non-inferior set has been generated for IEEE 14-bus systems using one of the intelligent optimization techniques, Particle Swarm Optimization (PSO). To solve the set of power flow equation to get the operating point of the system, the algorithm of Newton Raphson's method is adopted.

A MATLAB program has been developed for Evolutionary Programming and Evolutionary Computation such as Particle Swarm Optimization (PSO) to solve the problem addressing optimal placement and sizing of SVC considering the bus voltages and cost of installation.

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW:

With the evolution of modern civilization the demand of electrical energy has drastically increased. This wide spread use of electrical energy had demanded to produce it in bulk, economically and efficiently. This situation has forced the power system engineers to develop GRID SYSTEM i.e. the interconnection of several generating station located at different places. In present scenario the fast growth in power system grid could result in the difficulty for power system plant to cope with high demand. As power system is more complex and heavily loaded, voltage instability has become increasingly serious problem. The phenomenon of voltage instability in the electric power system can be characterized by a progressive decline of system voltage due to inability of the network in meeting increasing demand of reactive power. This problem of voltage instability may cause voltage collapse [6] [7] [9].

The phenomenon of voltage collapse on a transmission system is often caused by a low voltage profile, excessive demand, operation near the maximum power to be transmitted; generating stations located too far from demand or deficiency of reactive power compensation facilities. At first, a gradual voltage drop in one or several consumer regions may lead to increased reactive losses in the system and push transformer taps towards maximum values. Some generators or compensators can reach their limits of reactive power. In such a condition, voltage drops rapidly and it may drop substantially to cut off generating units and lines, one after the other thus causing a complete collapse of the system [11].

This problem can be overcome by proper compensation and expansion of power transmission capability. Compensation of reactive power using FACTS controllers can be suggested as one of the best solution in order to address the problem of voltage instability [16].

1.2 FLEXIBLE AC TRANSMISSION SYSTEMS:

The expansion of the transmission network has resulted in reduction of stability margins and increased the risks of cascading outages and blackouts. High power electronic controllers for the regulation of power flows and voltages in AC transmission networks are introduced to tackle this problem effectively. This allows 'flexible' operation of AC transmission systems whereby the changes can be accommodated easily without stressing the system. The system based on power electronics and other static equipment that provide controllability of power flow and voltages are termed as FACTS Controllers [2][3].

It is to be noted that power electronic controllers were first introduced in HVDC transmission for regulation of power flow in HVDC links, as well as for modulation to improve system stability i.e. both angle and voltage stability. The technology of thyristor valves and digital controls was initially extended to the development of Static Var Compensator (SVC) in long transmission lines for load compensation and voltage regulation. In 1988, Dr.Narain G. Hingorani introduced the concept of Flexible AC Transmission Systems (FACTS) by incorporating power electronic controllers to improve power transfer in existing AC transmission lines, voltage regulation and system security without adding new lines. These FACTS controllers can also be used to regulate power flow in critical lines and thus, ease congestion in electrical networks. The FACTS does not refer to any single device, rather a host of controllers such as SVC, Thyristor Controlled Series Capacitor (TCSC), Static Phase Shifting Transformer (SPST), and newer controllers based on Voltage Source Converters (VSC)-Static synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC) etc [4][5].

The advent of FACTS controllers has already made a major impact on the planning and operation of power delivery systems. The conceptualization of Custom Power by Dr.Hingorani in 1995 has extended the application of FACTS controllers for distribution systems with the objective of improving power quality.

1.3 PROPOSED METHODOLOGY:

Many areas in power systems, including the FACTS devices placement, control and sizing, require solving one or more nonlinear, multi-objective optimization problems. While analytical methods might suffer from slow convergence, heuristics based evolutionary computation techniques can be an efficient alternative to solve these complex optimization problems.

Particle swarm optimization (PSO) is an evolutionary computation technique developed by Russell Eberhart and James Kennedy in 1995, which is inspired by the social behavior of bird flocking and fish schooling. PSO has its roots in artificial life and social psychology as well as in engineering and computer science. It utilizes a “population” of particles that fly through the problem hyperspace with given velocities. At each iteration, the velocities of the individual particles are stochastically adjusted according to the historical best position for the particle itself and the neighborhood best position. Both the particle best and the neighborhood best is derived according to a user defined fitness function. The movement of each particle naturally evolves to an optimal or near-optimal solution.

PSO is known to effectively solve large scale nonlinear optimization problems. It is not largely affected by the size and nonlinearity of the problem, and can converge to the optimal solution in many problems where most analytical methods fail to converge. It can therefore be effectively applied to optimal location, sizing and control of FACTS devices in the power systems. Moreover, PSO has some advantages over other similar optimization techniques since:

(i) It is easier to implement and there are few parameters to adjust,

(ii) It has an effective memory capability, therefore it is able to perform an efficient search of the problem hyperspace, and

(iii) PSO maintains the diversity of the particles (more similar to the ideal social interaction in a community), thus it is capable to avoid getting trapped in local minima.

1.4 LITERATURE SURVEY:

Siti Amely Jummaat et al.(IEEE computer society, 2011 First International Conference on Informatics and Computational Intelligence) presented the application of Particle Swarm Optimization (PSO) and Evolutionary Programming (EP) technique for minimize the transmission loss and monitoring voltage profile and SVC installation cost. PSO and EP methods are applied on bus 26 and 29 of IEEE 30-Bus system. From the simulation results demonstrated that the proposed PSO technique is feasible for loss minimization scheme in power system network.

K Sundareswaran, et al.(2010 IEEE) identification of optimal location for placement of three SVC’s in IEEE 30 bus system is first formulated as an optimization problem and the solution is then achieved through the steps of Particle Swarm Optimization technique. The formulation of the problem and sequential step of PSO as applied to the problem are explained. The analysis of the simulation finding clearly indicates the effectiveness of the algorithm.

Muhammad Murtadha Othman et al.(IEEE Symposium on industrial Electronic and Application (ISIEA2011), Langkawi Malaysia) presents PSO technique for loss minimization in power system by using SVC. PSO is adopted to optimize the SVCs sizing to be installed in power transmission network. Tests are performed on the IEEE-26 bus RTS.

S.Sakthivel et al (Euro Journal Publishing, Inc.2011, ISSN Vol.66 No.3) explains PSO based optimization algorithm to solve the problem of optimal reactive power planning including the placement and sizing of SVC and TCSC device in a medium size power network for voltage stability limit improvement by controlling the reactive power flow and reducing the real power loss. Voltage stability limit improvement is more effective when it is done both by control of reactive power generation and reactive power flow. Reactive power generation control is indicated by the control of generator bus voltage and VAR support due to SVC. The effectiveness of the proposed work is tested on IEEE-30 bus test system under most critical line outage contingency condition.

Ahmed A. A. Esmin et al.(IEEE Transaction on POWER SYSTEM VOL.20,2005) presents a novel approach to optimize the power loss by using the PSO algorithm and expanding the original PSO to the HPSO algorithm. The Proposed approach utilizes the local and global capabilities to search for optimal loss reduction by installing the shunt compensator.

Rania Hassan et al. (American Institute of Aeronautics and Astronautics 2004) compared Particle Swarm Optimization and the Genetic Algorithm. Particle Swarm Optimization is a relatively recent heuristic search method that is based on the idea of collaborative behavior and swarming in biological population. PSO is similar to the Genetic Algorithm (GA) in the sense the they are both population-based search approaches and that they both depend on information sharing among their population member to enhance their search processes using combination of deterministic and probabilistic rules. The drawback of the GA is its expensive computational cost. This paper attempts to examine the claim that PSO has the same effectiveness (finding the true global optimal solution) as the GA but with significantly better computational efficiency (less function evaluations) by implementing statistical analysis and formal hypothesis testing. The performance comparison of the GA and PSO is implemented using a set of benchmark test problem as well as two space system design optimization problem, namely, telescope array configuration and spacecraft reliability based design.

A.H.Mantaway et al.(IEEE Bologna power Tech conference,2003) present Particle Swarm Optimization algorithm to minimize the active power losses in the network, while satisfying all the power system operation constraints. The particle Swarm Optimization has been coded as well as the power flow fast-decoupled method using MATLAB. The proposed algorithm has been successfully applied to the IEEE-6bus system. The simulation result shows that PSO algorithm always lead to a satisfactory result.

Thierry Van Custem (IEEE. Vol.88, No.2, Feb 2000) gives a description of the phenomena which contribute to voltage instability, to enumerate countermeasures, and to present in a (hopefully) unified and coherent way the computer analysis methods used or proposed.

John Paserba et al. (IEEE Transaction On POWER SYSTEM Vol.19 No.2, May 2004) defines power system stability more precisely, provide a systematic basis for its classification, and discuss linkages to related issues such as power system reliability and security. Definition of Power system Stability and detail classification of power system stability are presented. The relationship between the concepts of power system reliability, security and stability is discussed.

Luis Moran et al. (Invited Paper) presented an overview of the technological development of VAR generator and compensators. Starting from the principle of VAR compensation, classical solution using phase controlled semiconductors have been reviewed. The introduction of self-commutated topology based on IGBTs and IGCTs semiconductors produced a dramatic improvement in the performance of VAR compensation: they have faster dynamic behavior and they can control more Variables. The introduction of new self-commutated topologies at even higher voltage levels will increase the impact of VAR compensation in future applications. Some relevant example of project have been described, where it can be observed that modern VAR compensators improve power system performance, helping to increase reliability and the quality of power delivered to the customer.

Nang Sabai et al., **(World Academy of Science, Engineering and Technology, 2008),** "Voltage Control and Dynamic Performance of Power Transmission System Using Static Var Compensator" discuss and demonstrate how Static Var Compensator (SVC) has successfully been applied to control transmission systems dynamic performance for system disturbance and effectively regulate system voltage. The installation site for this paper is Hlawkar generation station in Myanmar. And data's will also be taken from this station. Simulation results will be provided by using MATLAB programming. The SVC is more effectively enhance the transient stability and increase transmission capacity.

Fang Liu et al.(International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009) presents a new rectifier system with a new SVC for the custom power systems. The new SVC contains the inductive filters, which can not only suppress the main harmonic currents generated by the TCR, but also suppress the main harmonic currents generated by the SCR, and shield them with the primary side and the power network, which is advantage to the operation of the rectifier transformer. Moreover, it can provide a certain reactive power near the SCR side. The detail simulation results verified the theoretical analysis, and express the good effects of the inductive filtering and the reactive power compensation that the new SVC has.

S. Auchariyamet, S. Sirisumrannukul , A PSO-based optimization technique has been developed in this paper to determine the optimal allocation of SVC and TCSC for reactive power planning. The case study is carried out with the modified IEEE 14-bus system. The study results show that SVC and TCSC are good choices to serve as Var sources for reactive power compensation because they can help reduce system real power loss and improve bus voltages. However in the view point of economic benefits, SVC and TCSC may not be appropriate as they are not cost-effective, at least, in the short term. However, it should be emphasized that SVC and TCSC can offer fringe benefits to the system, for example, system security and loadability improvement, voltage stability enhancement, system reliability increase, generation cost reduction. Such advantages should be quantified to justify the economic benefits of SVC and TCSC placement.

Ahmed Shawki Jaber , (Eng. & Tech. Journal, Vol.29, No.5, 2011), present the use of PSO to solve some kinds of two Variables function which submits to optimize function filed. A comparative study between PSO and GA to this kind of problems. The experimental results reported will shed more light into which algorithm is best in solving optimization problems.

Bindeshwar Singh .R et al.(International Journal of Engineering Science and Technology Vol. 2(5), 2010, 980-992). Presents comprehensive review of Various concept of voltage instability, main causes of voltage instability, classification of voltage stability, dynamic and static voltage stability analysis techniques, modeling, shortcomings, in power systems environments. It also reviews Various current techniques/methods for analysis of voltage stability in power systems through all over world.

S. Biansoongnern et al. (2006 International Conference on Power System Technology) presented a solution optimal placement of SVC and TCSC for minimization of transmission loss. The proposed of the new rank equation can be effectively used for the optimal placement of SVC and TCSC. The top priority ranked of lines and buses can be select for optimal placement of SVC and TCSC for minimization of transmission loss as compare to the sensitivity method. The optimal setting of TCSC and SVC include reactive power generator and tap transformer reduces the total real power loss.

N.M. Tabatabaei et al. (TPE-2008), present the location of a shunt FACTS device to improve transient stability in a long transmission line with predefined direction of real power flow. The validity of the mid-point location of shunt FACTS devices is verified, with different shunt FACTS devices, namely Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) in a long transmission line using the actual line model.

Dr. Ibrahim Oumarou, (Proceedings of the World Congress on Engineering 2009 Vol I WCE 2009, July 1 - 3, 2009, London, U.K,) investigates the effect of series compensation on the optimal location of a shunt FACTS device to get the highest possible benefit of maximum power transfer and system stability. Various results were found for an actual line model of a series compensated 345 kV, 450 km line. It has been found that the optimal location of the shunt FACTS device is not fixed as reported by many researchers in the case of uncompensated lines but it changes with the change in degree of series compensation. The deviation in the optimal location of the shunt FACT device from the centre point of line depends upon the degree of series compensation and it increases almost linearly from the centre point of the transmission line towards the generator side as the degree of series compensation (%S) is increased. Both the power transfer capability and stability of the system can be improved much more if the shunt FACTS device is placed at the new optimal location instead of at the mid-point of the line. The effect of SVC and STATCOM controllers in enhancing power system stability has been examined. Though both the devices can provide extra damping to the system, it has been demonstrated that STATCOM is very effective in enhancing system performance in situations where system voltages are very much depressed.

Shinichi Takayama et al. (IEEE Trans. on Power Systems, Vol.15, No.4, pp.1232- 1239, November 2001) presents a particle swarm optimization (PSO) for reactive power and voltage control (VVC) considering voltage security assessment (VSA). The proposed method formulates VVC as a mixed integer nonlinear optimization problem (MINLP) and determines a control strategy with continuous and discrete control Variables such as AVR operating values, OLTC tap positions, and the number of reactive power compensation equipment. The method also considers voltage security using a continuation power flow (CPFLOW) and a voltage contingency analysis technique.

Salman Mohagheghi et al.(IEEE Trans. on Evolutionary Computation, vol. 12, No. 2, April 2008) described the basic concepts of PSO along with its numerous Variants that can be employed in different optimization problems. In addition, a review of the applications of PSO in power systems-based optimization problems is presented to give the reader some insight of how PSO can serve as a solution to some of the most complicated engineering optimization problems.

T. K. Das, et al.(Student Member, IEEE) The optimal design of a SVC controller is presented using a small population based particle swarm optimization algorithm (SPPSO). The SPPSO algorithm is used to optimize the SVC PI controller parameters. These parameters provide better voltage stability than those parameters obtained by trial and error given the same cost function as that of SPPSO. The SPPSO algorithm has been implemented in a commercial power system simulation tool with detailed nonlinear models of the power system elements. The potential of the SPPSO algorithm is valuable for large power systems with multiple SVCs and other controllers where optimization of controller parameters is necessary to avoid any adverse effects. In such cases, linearized model based controller designs will not perform as desirable.

R. Benabida, et al.,(Electric Power Systems Research 79 (2009) 1668–1677), present a new method for optimal locating multi-type FACTS devices in order to optimize multiobjective voltage stability problem. The proposed methodology is based on a new Variant of particle swarm optimization (PSO) specialized in multi-objective optimization problem known as nondominated sorting particle swarm optimization (NSPSO).

N.G. Hingorani, and L. Gyugyi, (Understanding FACTS: Concept and technology of Flexible AC Transmission Systems, IEEE Press, 2000,) the concept of FACTS and FACTS controllers was first defined by Hingorani, 1988. FACTS usually refer to the application of high-power semiconductor devices to control different parameters and electrical Variables such as voltage, impedance, phase angles, currents, reactive and active power.

D. Gotham et al.(IEEE Transaction on Power Systems,vol.13,no.1 , 1998) FACTS can provide versatile benefits to transmission utilities such as control of power flow, increasing capabilities of lines to their thermal limits, reducing loop flows, providing greater flexibility .The value of FACTS application lies mainly in the ability of the transmission system to efficiently transmit power or to transfer power under contingency conditions [13].

T. Orfanogianni et al. (IEEE Transactions on Power Systems, vol. 18, no. 1, 2003.) As FACTS devices are costly so type, number and location of the FACTS devices is very important, to decide the optimal location and parameters of FACTS devices the following objective functions are used in FACTS related researches: Transmission pricing issues by maximizing social welfare with or without [14] consideration of FACTS' costs; Better utilization of FACT by maximizing FACTS devices total transferred power [15] Reactive power or voltage control by minimizing transmission losses [16], or voltage fluctuation [17]. Increase system's security under emergency by minimizing transmission lines loadability.

P. Lips et al. (CIGRE Technical Brochure 112, Paris, France, April 1997.), The heart of the SVC is an a.c. power semi-conductor switch commonly known as the "thyristor valve" that is used in principle to replace mechanical switches to achieve rapid, repetitive, and in some cases continuous control of the effective shunt susceptance at a specific location in a transmission system by a set of inductors and capacitors [18]. Fixed capacitor (FC) in parallel with a thyristor-controlled reactor (TCR), the valve continuously and "smoothly" controls the reactor to achieve a "net susceptance" that is varied to maintain the transmission system voltage to a desired value or range.

Sauer, Peter W. and Pai, M. A. ("Power System Dynamics and Stability" New Jersey Prenitice Hall, 1998) the power flow or load flow is widely used in power system analysis. It plays a major role in planning the future expansion of the power system as well as helping to run existing systems to run in the best possible way. The network load flow solution techniques are used for steady state and dynamic analysis programs.

J. Verseille, Convenor, (CIGRE Task Force 39.02, "Voltage and Reactive Control", Electra No. 173, August 1997) discusses the results of an electric utility survey on the practices that utilities use for transmission operational planning studies with respect to voltage limits and reactive margins to ensure adequate system security and reliability. This report outlines the general process that utilities use to determine system voltage limits and reactive power margins required to prevent voltage collapse (for example) for different system conditions such as peak and light loading, and contingency outages of transmission lines and/or generators. System and device modelling is also discussed in this report.

H. Amhriz-pbrez et al. (IEEE transactions on Power Systems. Vol. 15, No. 1, February 2000) focuses on the development of new SVC models and their implementation in Newton-Raphson load flow and optimal power flow algorithms. The SVC is taken to be a continuous, Variable-shunt susceptance, which is adjusted in order to achieve a specified voltage magnitude while satisfying constraint conditions.

Chapter 2

IDENTIFICATION OF WEAK BUS USING LOAD FLOW ANALYSIS

2.1 STUDY OF LOAD FLOW ANALYSIS:

Load-flow studies are very common in analysis of power system. We can find the present state of a system using load flow, given previous known parameters and values. The power that is being generated by the generators, the power that is flowing through the transmission line, the power that is being consumed by the loads, losses occurring during the transfer of power from source to load etc are iteratively decided by the load flow solution, also known as power flow solution. For any system, the most important quantity which is known or which is to be determined is the voltage at different points throughout the system. Knowing these, we can easily find out the currents flowing through each node or branch. This in turn gives us the quantities through which we can find out the power that is being handled at all these points.

In earlier days, small working models were used to find out the power flow solution for any network. Because computing these quantities was a hard task, the working models were not very useful in simulating the actual one. As a matter of fact it is difficult to analyze a system where we need to find out the quantities at a point very far away from the point at which these quantities are known. Thus we need to make use of iterative mathematical solutions to do this task, due to the fact that there are no finite solutions to load flow. Mathematical algorithms are used to compute the unknown quantities from the known ones through a process of successive trial and error methods and consequently produce a result.

In power system powers are known rather than currents. Thus the resulting equations in terms of power, known as power flow equation, become non linear and must be solved by iterative techniques. Power flows studies, commonly referred to as load flow, are the backbone of power system analysis and design, and they are necessary for planning & operation of power system, economic scheduling and exchange of power between utilities.

Power flow analysis is also required for many other analyses such as transient stability and contingency studies.

Load-flow analysis produces the following information:

(i). Voltage magnitude and phase angle at each bus.

(ii). Real and reactive power flowing in each element.

(iii). Reactive power loading on each generator.

2.1.1 BUSES CLASSIFICATION:

In a power system each bus or node is associated with four quantities. These quantities are real power, reactive power, bus voltage magnitude and bus voltage phase angle. At any bus two out of these four quantities are specified and rest two is to be obtained by load flow solution. Based on which quantity is specified at the bus, the buses are classified in the following three categories:

1.Load bus /PQ bus: Real power and reactive power is specified at this bus. Voltage magnitude and voltage phase angle is to be obtained through the load flow solution. Here we need to specify only real and reactive power demand at the load bus and the bus voltage magnitude is allowed to vary within the permissible limits. Phase angle is also not very important for the load bus.

2.Generator bus/ Voltage Controlled bus/ PV bus: The voltage magnitude corresponding to the generation voltage and the real power P_G corresponding to the rating of generator are specified. The reactive power at bus and the phase angle of the voltages is to be obtained through load flow solutions.

3.Slack bus/ Swing bus/ Reference bus: There are mainly two types of buses in the power system: load buses and generator buses. We have specified real power injections P_i for these buses. This power injection P_i at the bus is taken positive for generators and negative for load. Now $\sum_{i=1}^{n}$ Pi = real power loss P_L. This loss P_L remains unknown until the load flow solution is complete. For this reason one of the generator bus is made to take additional real and reactive power to supply transmission losses, thus this type of bus is also known as the slack or swing bus.

The voltage magnitude V and the phase angle δ are specified at this bus where as the active and reactive power is to be obtained through load flow solutions.

Table 2.1: Type of Buses

S.No.	Bus Type	Quantities Specified	Quantities to be Obtained
1.	Load	Active Power (P) Reactive Power (Q)	Voltage Magnitude ($\|V\|$) Phase Angle (δ)
2.	Generator	Active Power P Voltage Magnitude ($\|V\|$)	Reactive Power (Q) Phase Angle (δ)
3.	Slack	Voltage Magnitude ($\|V\|$) Phase Angle (δ)	Active Power (P) Reactive Power (Q)

If we are given any of the two inputs of the system, along with the fixed parameters like impedance of the transmission lines as well as that of the system, and system frequency, then using mathematical iterations we can easily find out the unknown Variables. Thus the operating state of the system can be determined easily knowing the two Variables.

2.1.2 ADMITTANCE MATRIX:

Current injection at a bus is analogous to power injection. Current injections may be either positive (going into the bus) or negative (coming out of the bus). Unlike current flowing through a branch (and thus is a branch quantity), a current injection is a nodal quantity. Fig. 2.1 shows a network represented in a hybrid fashion using one-line diagram representation for the nodes (buses 1-3) and circuit representation for the branches connecting the nodes and the branches to ground. The branches connecting the nodes represent lines. The branches to ground represent any shunt elements at the buses, including the charging capacitance at either end of the line. All branches are denoted with their admittance values y_{ij} for a branch connecting bus i to bus j and y_i for a shunt element at bus i. The current injections at each bus i are denoted by I_i.

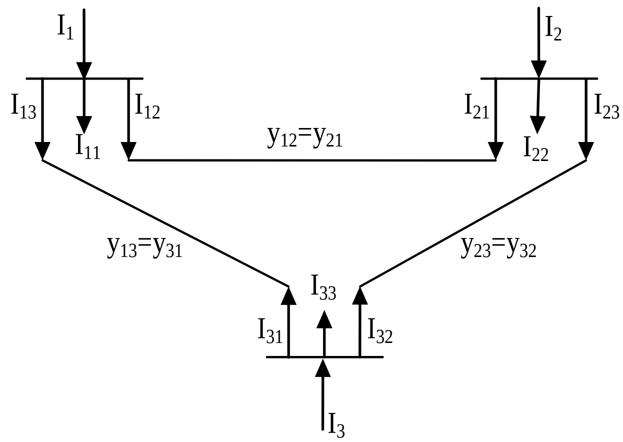

Fig. 2.1: Network for Modeling of Admittance Matrix

Kirchhoff's Current Law (KCL) requires that each of the current injections be equal to the sum of the currents flowing out of the bus and into the lines connecting the bus to other buses, or to the ground. Therefore, recalling Ohm's Law, $= \frac{Y}{Z} =$ Vy , the current injected into bus 1 may be written as:

$$I_1 = I_{11} + I_{12} + I_{13}$$
$$I_1 = V_1\, y_{11} + (V_1 - V_2)\, y_{12} + (V_1 - V_3)\, y_{13}$$
$$I_1 = V_1\, (y_{11} + y_{12} + y_{13}) - V_2\, y_{12} - V_3 y_{13}$$
$$I_1 = V_1\, y_{11} + V_1 y_{12} - V_2\, y_{12} + V_1 y_{13} - V_3 y_{13}$$
$$I_1 = V_1\, Y_{11} + V_2\, Y_{12} + V_3 Y_{13} \qquad \text{…….. (2.1)}$$

Thus, $Y_{11} = y_{11} + y_{12} + y_{13}$

$Y_{12} = -y_{12}$

$Y_{13} = -y_{13}$

Here, y_{11} is the line charging admittance between bus 1 and ground.

In general we may consider that each bus is connected to all other buses. The advantage to doing this is that it allows us to consider that bus 1 could be connected to any bus in the network.

Similarly the current injected into bus 2 may be written as:

$$I_2 = I_{21} + I_{22} + I_{23}$$
$$I_2 = V_2\, y_{22} + (V_2 - V_1)\, y_{21} + (V_2 - V_3)\, y_{23}$$
$$I_2 = V_2\, y_{22} + V_2 y_{21} - V_1\, y_{21} + V_2 y_{23} - V_3 y_{23}$$
$$I_2 = -V_1\, y_{21} + V_2\,(y_{21} + y_{22} + y_{23}) - V_3 y_{23}$$
$$I_2 = V_1\, Y_{21} + V_2\, Y_{22} + V_3 Y_{23} \qquad \text{…….. (2.2)}$$

Where;

$$Y_{21} = -y_{21}$$
$$Y_{22} = y_{21} + y_{22} + y_{23}$$
$$Y_{23} = -y_{23}$$

Similarly the current injected into bus 3 may be written as:

$$I_3 = I_{31} + I_{32} + I_{33}$$
$$I_3 = V_3\, y_{33} + (V_3 - V_1)\, y_{31} + (V_3 - V_2)\, y_{32}$$
$$I_3 = V_3\, y_{33} + V_3 y_{31} - V_1\, y_{31} + V_3 y_{32} - V_2 y_{32}$$
$$I_3 = -V_1\, y_{31} - V_2 y_{32} + V_3(y_{31} + y_{32} + y_{33})$$
$$I_3 = V_1\, Y_{31} + V_2\, Y_{32} + V_3 Y_{33} \qquad \text{…….. (2.3)}$$

Where;

$$Y_{31} = -y_{31}$$
$$Y_{32} = -y_{32}$$
$$Y_{33} = y_{31} + y_{32} + y_{33}$$

Where we recognize that the admittance of the circuit from bus k to bus i is the same as the admittance from bus i to bus k, i.e., yki=yik. From equs. (2.3) and (2.4), we see that the current injections are linear functions of the nodal voltages. Therefore, we may write these equations in a more compact form using matrices. These equations can be written in matrix form:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

We make several observations about the admittance matrix given in eqs. (2.6) and (2.7). These observations hold true for any linear network of any size.

1. The matrix is symmetric, i.e., Yij=Yji.

2. A diagonal element Yii is obtained as the sum of admittances for all branches connected to bus i, including the shunt branch, i.e $Y_{ii} = y_i + \sum_{k=1,k\neq i}^{N} y_{ik}$. Here we emphasize once again that yik is non-zero only when there exists a physical connection between buses i and k.

3. The off-diagonal elements are the negative of the admittances connecting buses i and j, i.e., Yij=-yji.

These observations enable us to formulate the admittance matrix very quickly from the network based on visual inspection. The following example will clarify.

2.1.3 POWER FLOW EQUATION:

Consider a typical bus of a Power system network as shown in Figure 2.3. Transmission line are represented by their equivalent π models where impedances have been converted to per unit admittances on a common MVA base.

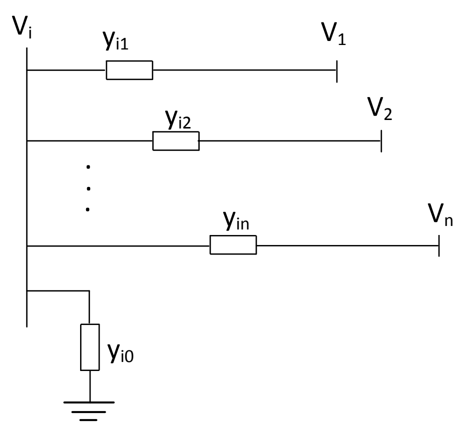

Fig 2.2: Typical bus of a power system network.

Application of KCL to this bus result in:

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \ldots\ldots + y_{in}(V_i - V_n)$$

$$I_i = (y_{i0} + y_{i1} + y_{i2} + \ldots\ldots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \ldots\ldots - y_{in}V_n$$

$$I_i = Y_{ii}V_i + \sum_{j=1,j\neq i}^{n} Y_{ij}V_j \qquad \ldots\ldots\ldots\ldots(2.4)$$

In the above equation, j includes bus i. Expressing this equation in polar form, we have

Let us define

$Y_{ii} = (y_{io} + y_{i1} + y_{i2} + \dots + y_{in})$

$Y_{i1} = - y_{i1}$

$Y_{i2} = -y_{i2}$

.

.

.

$Y_{in} = -y_{in}$

The real and reactive power injected at bus i is given as:

$S^* = V_i^* I_i = P_i – j Q_i$

$$I_i = \frac{Pi – j\ Qi}{Vi*} \qquad \text{.........(2.5)}$$

Comparing the equations (2.4) & (2.5) we get:

$$\frac{Pi – j\ Qi}{Vi*} = Y_{ii}V_i + \sum_{j=1, j\neq i}^{n} Y_{ij} V_j$$

$$P_i – j Q_i = V_i^* \{ Y_{ii}V_i + \sum_{j=1, j\neq i}^{n} Y_{ij} V_j \} \qquad \text{.........(2.6)}$$

Let,

$V_i = |V_i| \angle \delta_i$

$Y_{ij} = |Y_{ij}| \angle \Theta_{ij}$

$$P_i – j Q_i = |V_i||V_j||Y_{ij}| \angle (\delta_j + \Theta_{ij} - \delta_i) \qquad \text{.........(2.7)}$$

Comparing the real and imaginary part of both side of the above equation we get:

$$P_i = |V_i||V_j||Y_{ij}| \cos(\delta_j + \Theta_{ij} - \delta_i) \qquad \text{.........(2.8)}$$

$$Q_i = –|V_i||V_j||Y_{ij}| \sin(\delta_j + \Theta_{ij} - \delta_i) \qquad \text{.........(2.9)}$$

Above two equations constitute a set of non linear algebraic equations in terms of independent Variables, voltage magnitude in per unit, and phase angle in radians. Expanding above two equations in Taylor series about initial estimate and neglecting all higher order terms results in the following set of equations:

$$\begin{bmatrix} \Delta P2 \\ \vdots \\ \Delta Pn \\ \Delta Q2 \\ \vdots \\ \Delta Qn \end{bmatrix} = \begin{bmatrix} \frac{\partial P2}{\partial \delta 2} & \cdots & \frac{\partial P2}{\partial \delta n} & \frac{\partial P2}{\partial |V2|} & \cdots & \frac{\partial P2}{\partial |Vn|} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial Pn}{\partial \delta 2} & \cdots & \frac{\partial Pn}{\partial \delta n} & \frac{\partial Pn}{\partial |V2|} & \cdots & \frac{\partial Pn}{\partial |V2|} \\ \frac{\partial Q2}{\partial \delta 2} & \cdots & \frac{\partial Q2}{\partial \delta n} & \frac{\partial Q2}{\partial |V2|} & \cdots & \frac{\partial Q2}{\partial |Vn|} \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial Qn}{\partial \delta 2} & \cdots & \frac{\partial Qn}{\partial \delta n} & \frac{\partial Qn}{\partial |V2|} & \cdots & \frac{\partial Qn}{\partial |V2|} \end{bmatrix} \begin{bmatrix} \Delta \delta 2 \\ \vdots \\ \Delta \delta n \\ \Delta |V2| \\ \vdots \\ \Delta |Vn| \end{bmatrix} \quad \ldots\ldots\ldots (2.10)$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |Vn| \end{bmatrix} \quad \ldots\ldots\ldots (2.11)$$

In the above equation BUS1 is assumed to be slack bus. The jacobian matrix gives the linearized relationship between small changes in active power (ΔP) and reactive power (ΔQ) due to the small changes in voltage magnitude (Δ|V|) and phase angle (Δδ).

Elements of the jacobian matrix are the partial derivatives of equation (2.8) & (2.9) with respect to voltage magnitude (|V|) and voltage phase angle (δ) and can be expressed as:

The diagonal and off diagonal element of matrix J1 is given by:

$$\frac{\partial Pi}{\partial \delta i} = \sum_{n=1, n\neq i}^{N} Vi\, Vn\, Yin \sin(\delta i - \delta n - \Theta in) \quad \ldots\ldots\ldots (2.12)$$

$$\frac{\partial Pi}{\partial \delta j} = Vi\, Vj\, Yij \sin(\delta i - \delta j - \Theta ij)\,; \qquad i \neq j \quad \ldots\ldots\ldots (2.13)$$

The diagonal and off diagonal element of matrix J2 is given by:

$$\frac{\partial Pi}{\partial |Vi|} = 2Vi\, Yii\, cos\Theta ii + \sum_{n=1, n\neq i}^{N} Vn\, Yin \cos(\delta i - \delta n - \Theta in) \quad \ldots\ldots (2.14)$$

$$\frac{\partial Pi}{\partial |Vj|} = Vi\, Yij \cos(\delta i - \delta j - \Theta ij); \qquad i \neq j \quad \ldots\ldots\ldots (2.15)$$

The diagonal and off diagonal element of matrix J3 is given by:

$$\frac{\partial Qi}{\partial \delta i} = \sum_{n=1, n\neq i}^{N} Vi\, Vn\, Yin\, \mathrm{COS}(\delta i - \delta n - \Theta in) \quad \ldots\ldots\ldots (2.16)$$

$$\frac{\partial Qi}{\partial \delta j} = \ Vi\, Vj\, Yij \cos(\delta i - \delta j - \Theta ij)\, ; \qquad i \neq j \qquad \ldots\ldots\ldots (2.17)$$

The diagonal and off diagonal element of matrix J4 is given by:

$$\frac{\partial Qi}{\partial |Vi|} = \ 2Vi\, Yii\, sin\Theta \text{ii} + \sum_{n=1, n\neq i}^{N} Vn\, Yinsi\, n(\delta i - \delta n - \Theta in) \quad \ldots\ldots\ldots (2.18)$$

$$\frac{\partial Qi}{\partial |Vj|} = \ Vi\, Yij \sin(\delta i - \delta j - \Theta ij); \qquad i \neq j \qquad \ldots\ldots\ldots (2.19)$$

The term ΔP_i and ΔQ_i are the differences between specified and calculated values of real and reactive powers and are known as power residues.

$$\Delta P_i^{(k)} = P_{i(specifies)} - P_i^{(k)}{}_{(calculated)} \qquad \ldots\ldots\ldots (2.20)$$

$$\Delta Q_i^{(k)} = Q_{i(specifies)} - Q_i^{(k)}{}_{(calculated)} \qquad \ldots\ldots\ldots (2.21)$$

The bus values can be updated as follows:

$$V_i^{(k+1)} = V_i^{(k)} + \Delta V_i^{(k)} \qquad \ldots\ldots\ldots (2.22)$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \qquad \ldots\ldots\ldots (2.23)$$

2.1.4 ALGORITHM FOR NEWTON RAPHSON METHOD OF LOAD FLOW ANALYSIS:

The procedure for power flow solution by the Newton-Raphson method is as follows:

1. For load buses, where P and Q are specified, voltage magnitudes and phase angles are set equal to the slack bus values, or 1.0 and 0.0 i.e.$|V_i^{(0)}| = 1.0$ and $\delta_i^{(0)} = 0$.
2. For load buses $P_i^{(k)}$ & $Q_i^{(k)}$ are calculated from equations (2.8) & (2.9) and ΔP_i & ΔQ_i are calculated from equations (2.20) & (2.21).
3. For generator buses $P_i^{(k)}$ and $\Delta P_i^{(k)}$ are calculated from equations (2.8) & (2.20).
4. The elements of the Jacobian matrix are calculated from (2.12) to (2.19).
5. The linear simultaneous equations represented in the form of matrix in equation (2.10) are solved to get $\Delta V_i^{(k)}$ & $\Delta\delta_i^{(k)}$.
6. The new voltage magnitudes and phase angles are computed from (2.22) and (2.23).
7. The process is continued until the residuals $\Delta P_i^{(k)}$ & $\Delta Q_i^{(k)}$ are less than the specified accuracy i.e.:

$$\Delta P_i^{(k)} \leq \varepsilon \qquad \& \qquad \Delta Q_i^{(k)} \leq \varepsilon$$

2.2 IDENTIFICATION OF THE WEAK LOAD BUSES:

From Equation (2.11) :

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|Vn| \end{bmatrix}$$

By letting ΔP = 0, from equation 2.11 we get:

$\Delta P = 0 = J1\Delta\delta + J2\Delta V$ ....(2.24)

$\Delta\delta = - J1^{-1} (J2\Delta V)$

$\Delta Q= J3\Delta\delta + J4\Delta V$

Substituting the Δδ in above equation:

$\Delta Q= J3(- J1^{-1} (J2\Delta V)) + J4\Delta V$

$\Delta Q=J_R\, \Delta V$

Where $J_R = J4 – J3\, (J1)^{-1}\, J2$

J_R is the reduced jacobian matrix of the system.

The matrix J_R represents the linearized relationship between the incremental changes in bus Voltage (ΔV) and bus reactive power injection (ΔQ). It's well known that, the system voltage is affected by both real and reactive power Variations. In order to focus the study of the reactive demand and supply problem of the system as well as minimize computational effort by reducing dimensions of the Jacobian matrix J the real power (ΔP = 0) and angle part from the system in Equation (2.24) are eliminated.

The eigen values and eigenvectors of the reduced order Jacobian matrix JR are used for the voltage stability characteristics analysis. Voltage instability can be detected by identifying modes of the eigen values matrix JR. The magnitude of the eigen values provides a relative measure of proximity to instability. The eigenvectors on the other hand present information related to the mechanism of loss of voltage stability.

Eigen value analysis of J_R results in the following:

$J_R^{-1} = \Phi\, \wedge^{-1}\, \Gamma$ ....(2.25)

Where:

Φ is right eigen vector matrix of J_R

∧ is diagonal eigen vector matrix of J_R

Γ is left eigen vector matrix of J_R

Equation (2.25) can be written as

$$\Delta V = \Phi \wedge^{-1} \Gamma_i \Delta Q$$

$$\Delta V = \sum_{i=0}^{n} \frac{\Phi i \, \Gamma i}{\lambda i} \quad \text{……… (2.26)}$$

Where λ_i is the i_{th} eigen value, Φ_i is the i_{th} column of right eigen value and Γ_i is the i_{th} row left eigenvector of matrix J_R.

Each eigen value λ_i and corresponding right and left eigenvectors Φ_i and Γ_i define the i_{th} mode of the system. The i_{th} modal reactive power variation is defined as:

$\Delta Q_{mi} = K_i \Phi_i$

Where K_i is a scale factor to normalize vector ΔQ_i so that

$$K_i^2 \sum_i \Phi_{ji}^2 = 1 \quad \text{………(2.27)}$$

With Φ_{ji} the j_{th} element of Φ_i.

The corresponding i_{th} modal voltage Variation is:

$$\Delta V_{mi} = \frac{1}{\lambda i} \Delta Q_{mi} \quad \text{……….(2.28)}$$

Equation (2.39) can be summarized as follows:

(i). If $\lambda_I = 0$, the i_{th} modal voltage will collapse because any change in that modal reactive power will cause infinite modal voltage Variation.

(ii). If $\lambda_i > 0$, the i_{th} modal voltage and i_{th} reactive power Variation are along the same direction, indicating that the system is voltage stable.

(iii). If $\lambda_i > 0$, the i_{th} modal voltage and the i_{th} reactive power Variation are along the opposite directions, indicating that the system is voltage unstable.

In general it can be said that, a system is voltage stable if the eigen values of J_R are all positive. This is different from dynamic systems where eigen values with negative real parts are stable. The relationship between system voltage stability and eigen values of the J_R matrix is best understood by relating the eigen values with the V-Q sensitivities of each bus (which must be positive for stability). J_R can be taken as a symmetric matrix and therefore the eigen values of J_R are close to being purely real. If all the eigen values are positive, J_R is positive definite and the V-Q sensitivities are also positive, indicating that the system is voltage stable.

The system is considered voltage unstable if at least one of the eigen values is negative. A zero eigen value of J_R means that the system is on the verge of voltage instability.

Furthermore, small eigen values of J_R determine the proximity of the system to being voltage unstable. There is no need to evaluate all the eigen values of J_R of a large power system because it is known that once the minimum eigen values becomes zeros the system Jacobian matrix becomes singular and voltage instability occurs. So the eigen values of importance are the critical eigen values of the reduced Jacobian matrix J_R. Thus, the smallest eigen values of J_R are taken to be the least stable modes of the system. The rest of the eigen values are neglected because they are considered to be strong enough modes. Once the minimum eigen values and the corresponding left and right eigenvectors have been calculated the participation factor can be used to identify the weakest node or bus in the system.

The minimum eigen values, which become close to instability, need to be observed more closely. The appropriate definition and determination as to which node or load bus participates in the selected modes become very important. This necessitates a tool, called the participation factor, for identifying the weakest nodes or load buses that are making significant contribution to the selected modes. If ϕ_i and Γ_i represent the right- and left hand Eigen vectors, respectively, for the eigen value λ_i of the matrix J_R, then the participation factor measuring the participation of the k_{th} bus in i_{th} mode is defined as:

$$P_{ki} = \phi_{ki} \Gamma_{ki} \quad \text{………(2.29)}$$

Note that for all the small eigen values, bus participation factors determine the area close to voltage instability. Equation (2.29) implies that P_{ki} shows the participation of the i_{th} eigen value to the V-Q sensitivity at bus k. The node or bus k with highest P_{ki} is the most contributing factor in determining the V-Q sensitivity at i_{th} mode. Therefore, the bus participation factor determines the area close to voltage instability provided by the smallest eigen value of J_R.

Chapter 3

VOLTAGE PROFILE IMPROVEMENT USING STATIC VAR COMPENSATOR

3.1 INTRODUCTION:

The modern power system is more complex due to change in the system configuration day to day, to meet the increasing demand in electrical energy by installing the new generating units, interconnection of transmission lines and extra high voltage tie line etc. In modern power system, reactive power compensation voltage stability problems (voltage fluctuations) and Power oscillations due to faults and sudden load disturbances are major issues. One more challenge to the engineers is to improve reliability and efficiency of the existing systems. To get both financial profitability and operational reliability, the existing power systems require the infrastructure for more efficient utilization and control. Improved utilization and control is possible with advanced control technologies. FACTS controllers are advanced technology devices widely used to efficiently utilize the existing power system and also used to enhance the dynamic performance and stability of the power system.

The Static Var Compensator is the first generation of FACTS devices that has been in use in transmission systems in late 1970s, the use of SVCs in transmission system has been increasing steadily. Static Var compensator is shunt-connected static generator and/or absorber whose output are Varied so as to control specific parameters of the electric power system. The term "static" is used to indicate that SVC's, unlike synchronous compensators, have no moving or rotating main components. Thus svc consists of static Var generator (SVG) or absorber devices and a suitable control device. The SVC provides an excellent source of rapidly controllable reactive shunt compensation for dynamic voltage control through its utilization of high-speed thyristor switching/controlled reactive devices.

3.2 REASONS FOR INSTALLATION OF SVCS IN POWER SYSTEM:

1. Voltage regulation: The main reason that SVCs are installed in power system is to control the voltage within required levels. Load Varies over the day, with very low load from midnight to

early morning and peak values occurring in the evening between 4 PM and 7 PM. Shape of the load curve also Varies from weekday to weekend, with weekend load typically low. As the load Varies, voltage of the load bus Varies. Since the load power factor is always lagging, a shunt connected SVC raise voltage when the load is high. The shunt SVCs can be switched as needed. Switching can be based on time, if load Variation is predictable, or can be based on voltage, power factor, or line current.

2. Reducing power losses: Compensating the load lagging power factor with the bus connected SVCs improves the power factor and reduces current flow through the transmission lines, transformers, generators, etc. This will reduce power losses (I2R losses) in this equipment. One of the main benefits of applying SVCs is that they can reduce distribution line losses. Losses come from current through the resistance of conductors. Some of that current transmits real power, but some flows to supply reactive power. Reactive power provides magnetizing for motors and other inductive loads. Reactive power does not spin kWh meters and performs no useful work, but it must be supplied. Using SVCs to supply reactive power reduces the amount of current in the line.

3. Increased utilization of equipment: SVCs with capacitor banks reduces kVA loading of lines, transformers, and generators, which means with compensation they can be used for delivering more power without overloading the equipment.

3.3 TYPES OF SVC:

The following are the basic type of reactive power control element which make up all or part of any static Var system:

- Saturated reactor (SR)
- Thyristor-controlled reactor (TCR)
- Thyristor-switched capacitor (TSC)
- Thyristor-switched reactor (TSR)
- Thyristor-controlled transformer (TCT)
- Self or line commutated converter (SCC/LCC)

An SVC is typically made up of the following major components:

- Coupling transformer
- Thyristor valves

• Reactors

• Capacitors (often tuned for harmonic filtering)

In general, the two thyristor valve controlled/switched concepts used with SVCs are the thyristor-controlled reactor (TCR) and the thyristor-switched capacitor (TSC). The TSC provides a “stepped” response and the TCR provides a “smooth” or continuously variable susceptance.

Two “common” main SVC circuit arrangements are:

1. FC/TCR”–fixed capacitor (filter)/thyristor (phase angle)-controlled reactor.
2. TSC/TCR”–thyristor-switched capacitor/thyristor-controlled reactor.

An SVC is a controlled shunt susceptance as defined by the SVC control settings that injects reactive power (Q) into the system based on the square of its terminal voltage. Fig 3.2 illustrates a TCR/FC SVC, including the operational concept. The control objective of the SVC is to maintain a desired voltage at the high-voltage bus. In the steady-state, the SVC will provide some steady-state control of the voltage to maintain it the high-voltage bus at a predefined level.

If the high-voltage bus begins to fall below its set point range, the SVC will inject reactive power (Qnet) into the system (within its controlled limits), thereby increasing the bus voltage back to its desired voltage level. If bus voltage increases, the SVC will inject less (or TCR will absorb more) reactive power (within its controlled limits), and the result will be to achieve the desired bus voltage. From Fig 3.2, +Qcap is a fixed capacitance value, therefore the magnitude of reactive power injected into the system, Qnet, is controlled by the magnitude of Qind reactive power absorbed by the TCR.

3.4 FUNDAMENTAL FREQUENCY PERFORMANCE OF AN SVC

Static Var systems are capable of controlling individual phase voltages of the buses to which they are connected. They can therefore be used for control of negative sequence as well as positive sequence voltage deviation. However, we are interested here in the balanced fundamental frequency performance of power system and therefore our analysis will consider only this aspect of SVC performance. Form the viewpoint of power system operation, an SVC is equivalent to a shunt capacitor and a shunt inductor, both of which can be adjusted to control voltage and reactive power at its terminals (or a nearby bus) in a prescribed manner.

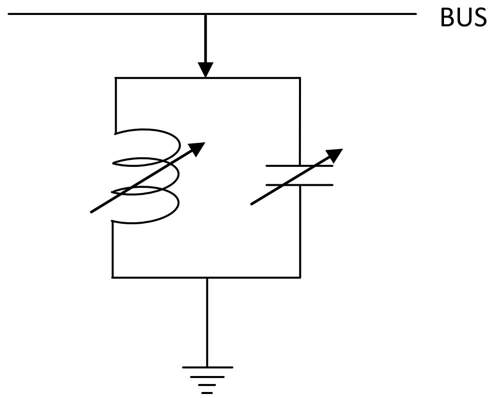

Fig 3.1: Idealized static Var system

Ideally, an SVC should hold constant voltage (assuming that this is the desired objective), posses unlimited Var generation /absorption capability with no active and reactive power losses and provide instantaneous response. The performance of the SVC can be visualized on graph of controlled ac bus voltage (V) plotted against the SVC reactive current (I_s).The V/I characteristics of an ideal SVC is shown in Fig 3.2.It represents the steady-state and quasi steady-state characteristics of the SVC.

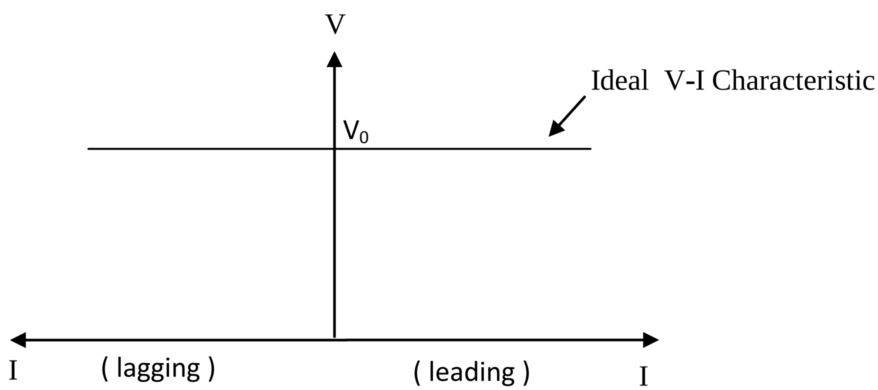

Fig3.2: V/I characteristic of ideal compensator

3.4.1 CHARACTERISTIC OF REALISTIC SVC:

We consider an SVC composed of a controllable reactor and a fixed capacitor. The resulting characteristics are sufficiently general and are applicable to a wide range of practical SVC configurations. Fig 3.6 illustrates the derivation of the characteristics of an SVC consisting of a controllable reactor and a fixed capacitor. The composite characteristic is derived by adding the individual characteristics of the components. The characteristic shown in fig3.5 (a) is representative of the characteristics of practical controllable reactors.Fig3.5 (b) is representative of the characteristics of practical capacitor. Fig3.3 is representative of the characteristics of practical static Var system.

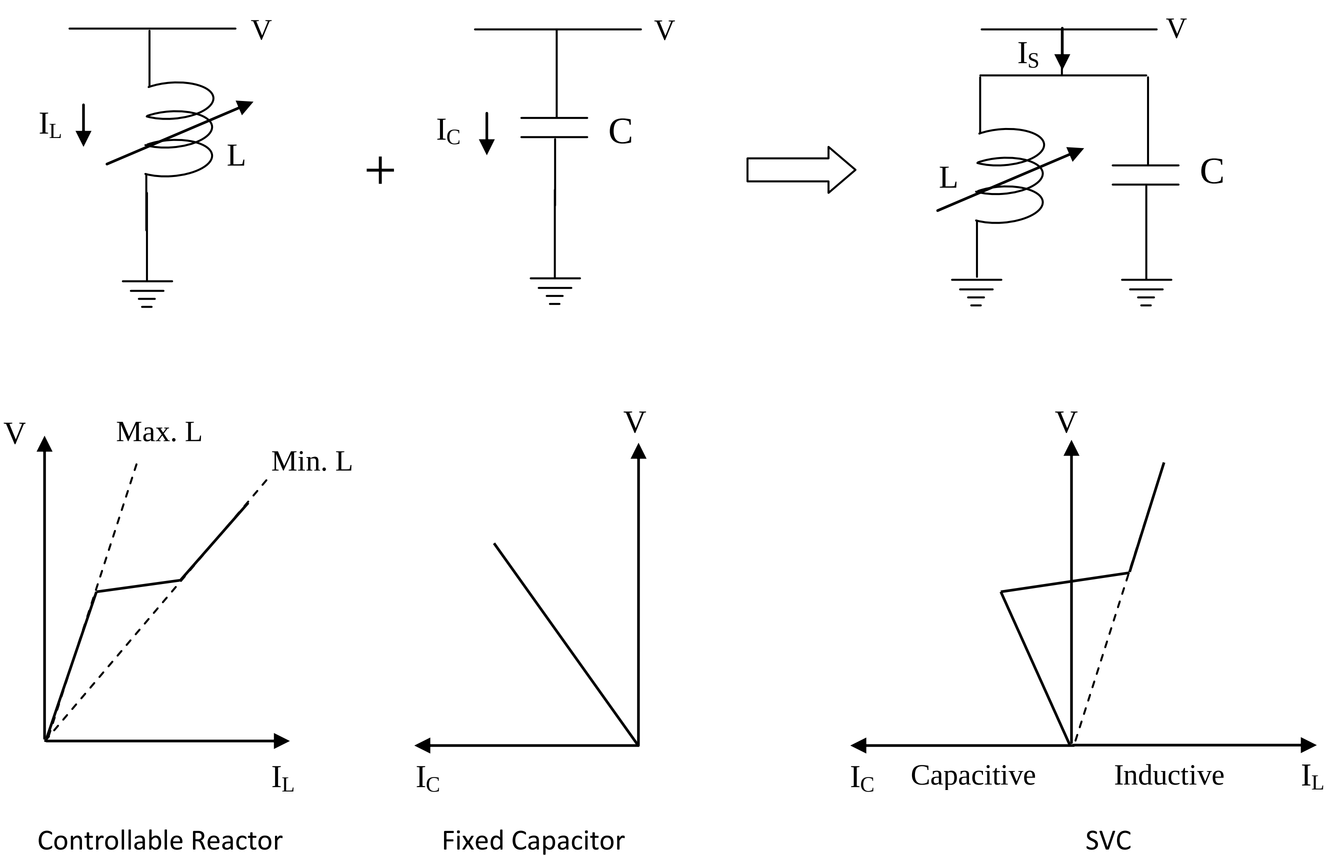

Fig 3.3 Composite Characteristics of an SVC

3.4.2 POWER SYSTEM CHARACTERISTICS:

In order to examine how the SVC performs when applied to a power system, the characteristics of the SVC and the power system need to be examined together. The system V/I characteristics may be determined by considering the Thevenin's equivalent circuit as viewed from the bus whose voltage is to be regulated by the SVC. This is illustrated in Fig 3.4.The Thevenin's impedance in Fig 3.4 (a) is predominantly an inductive reactance. The corresponding voltage versus reactive current characteristics is shown in Fig 3.4 (b). The voltage V increases linearly with capacitive load current and decreases linearly with inductive load current.

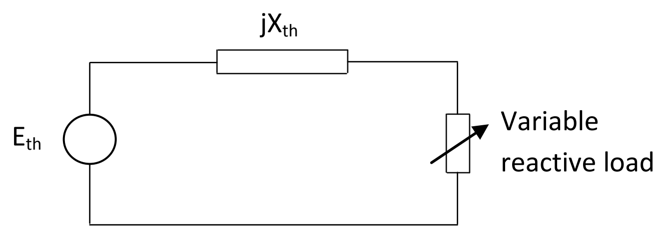

Fig 3.4(a) Thevenin equivalent circuit of HVAC network

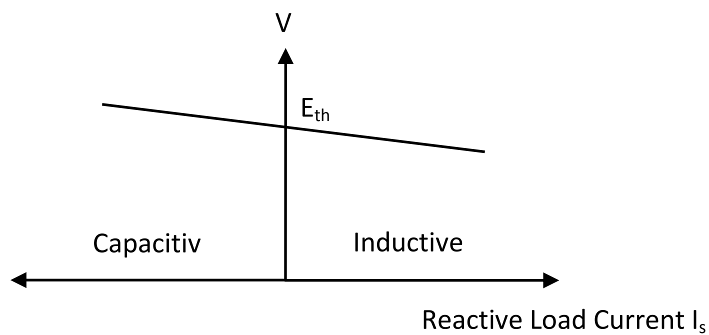

Fig 3.4(b) Voltage-Reactive Current Characteristics of HVAC System

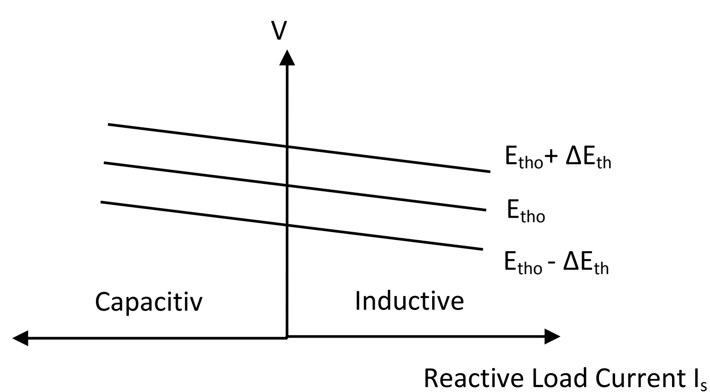

Fig 3.4(c) Effect of Varying Source Voltage E_{th}

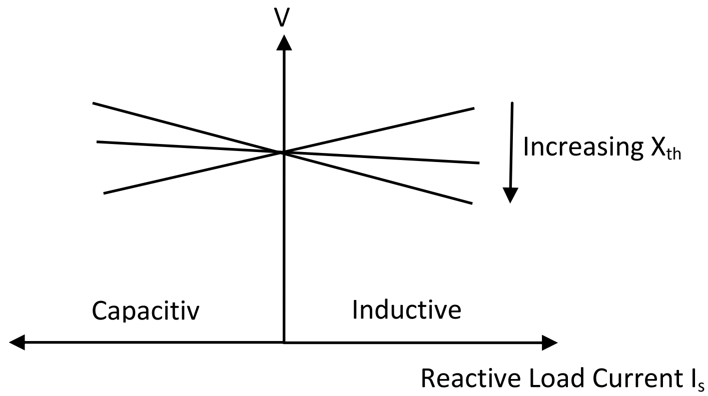

Fig 3.4(d) Effect of Varying System Reactance X_{th}

3.4.3 COMPOSITE SVC-POWER SYSTEM CHARACTERISTICS:

The system characteristics may be expressed as: $V=E_{th} - X_{th}I_s$

The SVC characteristics, within the control range defined by the slope reactance XSL is given by: $V = V_0 + X_{SL}\ I_S$ ……3.2

For voltage outside the control range, the ratio $\frac{V}{Is}$ is equal to the slopes of the two extreme segments. These are determined by the ratings of the inductor and capacitor. The solution of SVC and power system characteristics equation is graphically illustrated in Fig 3.5. Three system characteristics are considered in the Fig, corresponding to three values of the source voltage. The middle characteristics represented nominal condition, and is assumed to intersect the SVC characteristics at point A where $V = V_0$ and $I_S = 0$.

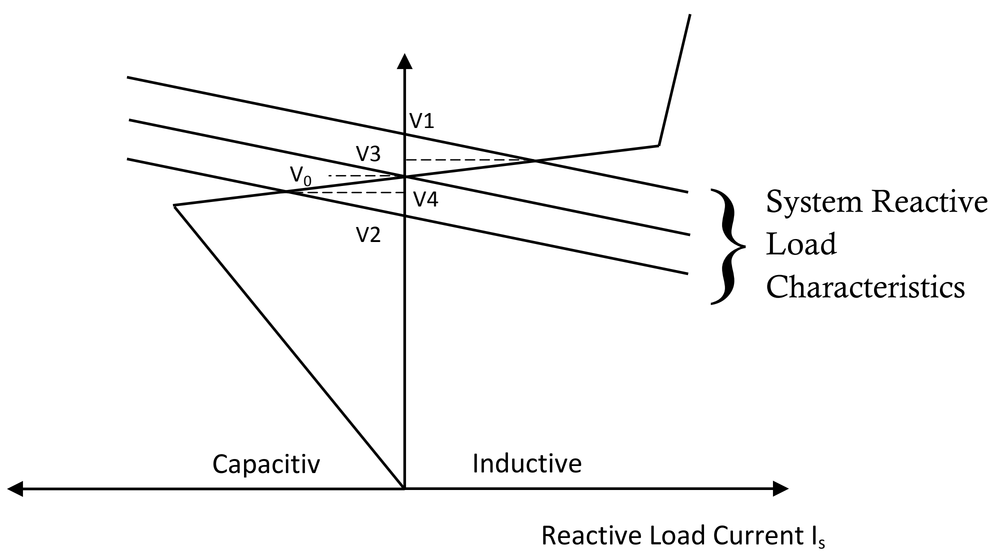

Fig 3.5 Graphical Solution of SVC Operating Point for Given System Condition

If the system voltage increases by ΔE_{th}, for example due to a decrease in system load level V will increase to V_1, without an SVC. With the SVC however, the operating point moves to B; by absorbing inductive current I_3, the SVC holds the voltage at V_3. Similarly, if the source voltage decreases (due to increase in system load level), the SVC holds the voltage at V4, instead of at V2 without the SVC. If the slope Ks of the SVC characteristics were zero, the voltage would have been held at V0 for both cases considered above.

Effect of using switched capacitor: In the example considered in Fig 3.6, the SVC control range would be exceeded for larger Variation in system condition. The use of switched capacitor banks can extend the continuous control range of the SVC. This illustrated in Fig 3.6, which considers three capacitor banks, two of which are switchable. Either thyristor or mechanical switches may be used for switching the capacitors in and out automatically by local voltage-sensing controls. In the Fig the unswitched capacitor includes a reactor for filtering harmonics. We see that an SVC is not a source of voltage as is a synchronous condenser. Instead, it alters the system voltage at the point of connection by varying the reactive current drawn or supplied to the system. In effect, the SVC acts as a Variable reactive load which is adjusted so as to keep the ac voltage nearly constant.

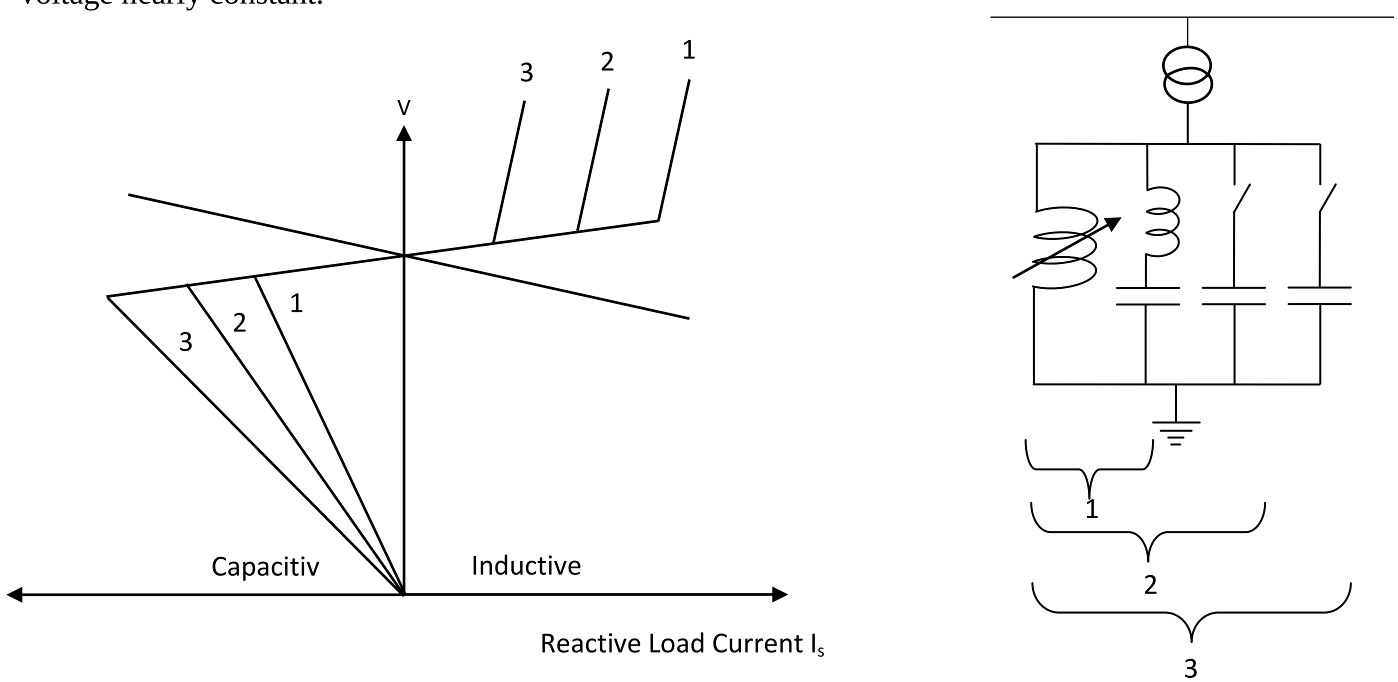

Fig 3.6 Use of Switched Capacitor to Extend Continuous Control Range

SVC can be made to generate or absorbed reactive power by means of Thyristor controlled element. It has the capability of supplying dynamically adjustable reactive power (by conduction time of thyristor) with in the upper and lower limit and can be modeled by a Variable shunt susceptance. The increases susceptance requirement is proportional to the higher cost of static Var system installation.

3.4.4 PRACTICAL STATIC VAR COMPENSATOR:

A static Var compensator scheme with any desired control range can be formed by using combination of Thyristor controlled reactor (TCR), Thyristor-switched capacitor (TSC), Mechanically switch capacitor (MSC).Several SVC configuration have been successfully applied to meet differing system requirements. The required speed of response, size range, flexibility, losses, and cost are among the important consideration in selecting a configuration for any particular application.

Fig 3.7 shows a typical SVC scheme consisting of a TCR, a three unit TSC, and harmonic filter (for filtering TCR-generated). At power frequency, the filters are capacitive and produce reactive power of about 10 to 30% of TCR MVar rating. In order to ensure smooth control characteristics, the TCR current rating should be slightly larger than that of one TSC unit; otherwise dead bands arise.

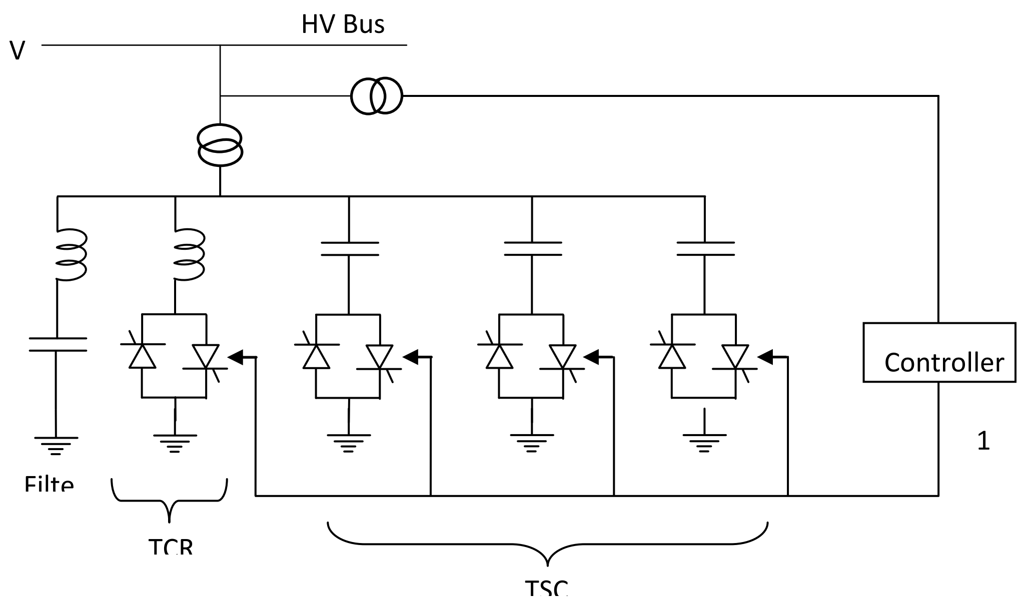

Fig 3.7 A Typical Static Var System

The steady-state V/I characteristics of the SVC is shown in Fig 3.8(a), and the corresponding $\frac{V}{Q}$ characteristics is shown in Fig 3.8(b). The linear control range lies within the limit determined by the maximum susceptance (B_{LMX}) of the reactor, the total capacitive susceptance (B_c) as determined by the capacitive banks in service and the filter capacitance. If the voltage drops below a certain level (typically 0.3pu) for an extended period, control power and thyristor gating energy can be lost, requiring a shutdown of the SVC. The SVC can restart as soon as the voltage recovers. However, the voltage may drop to low values for short periods, such as during transient faults, without causing SVC to trip. Within the linear control range, the SVC is equivalent to a voltage source V_{ref} in series with a reactance of XSL. The slope reactance XSL has a significant effect on the performance of the SVC.A large value of XSL makes the SVC less responsive, i.e., changes in system condition cause large voltage Variation at the SVC high voltage bus. The value of X_{SL} is determined by the steady-state gain of the controller (voltage regulator). It may also be affected by a current feedback (with PI controller). Its choice should be based on detailed power-flow and stability studies typically, the slope is set within the range of 1 to 5%, depending on the ac system strength.

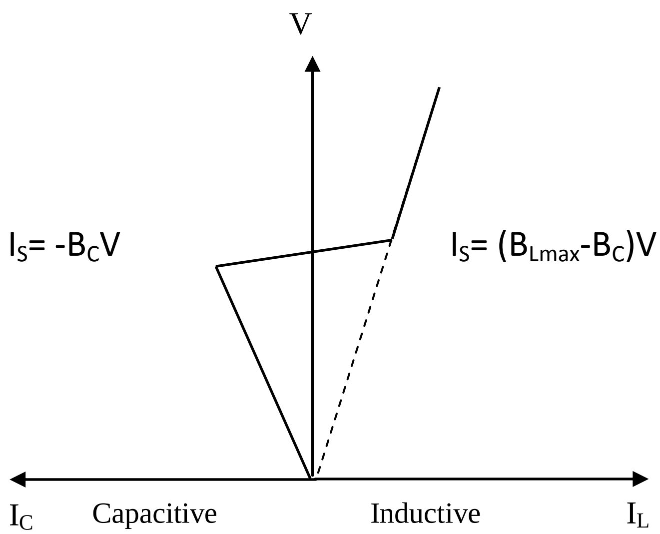

Fig 3.8 (a) Voltage Current Characteristics

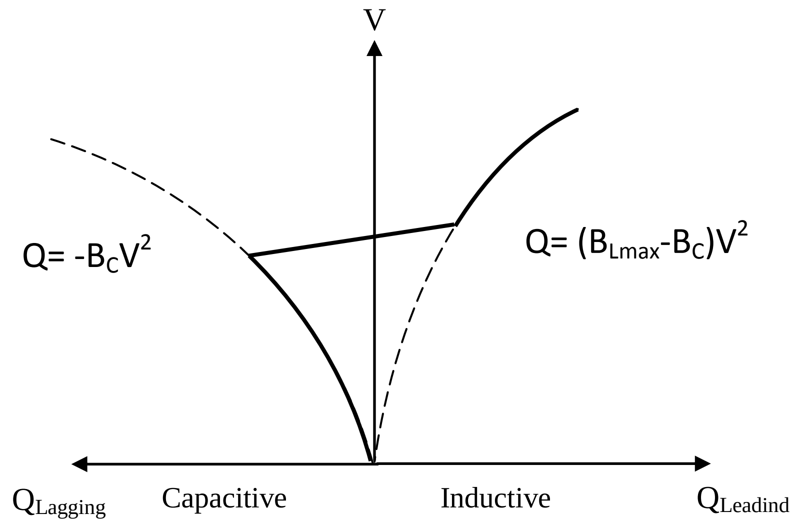

Fig3.8 (b) Voltage Reactive Power Characteristics

CHAPTER 4

PARTICLE SWARM OPTIMIZATION

4.1 INTRODUCTION:

In many engineering disciplines a large spectrum of optimization problem has grown in size and complexity. For some instances, the solution to complex multidimensional problem by means of classical optimization technique is extremely difficult and/or computational expensive. This realization has led to an increased interest in a special class of searching algorithms known as heuristic algorithms. They are referred to as "stochastic" optimization techniques and their foundation lie in the evolutionary patterns and behavior observed in living organisms.

PSO is a population-based, self-adaptive, stochastic optimization technique [36, 37]. The basic idea of PSO is the mathematical modelling and simulation of food searching activities of a swarm of birds (particles). In the multidimensional space where the optimal solution is sought, each particle in the swarm is moved towards the optimal point by adding a velocity to its position where the velocity of a particle is influenced by three components viz. inertial, cognitive, and social component. The inertial component simulates the inertial behaviour of the bird to fly in the previous direction, cognitive component models the memory of the bird about its previous best position and the social component models the memory of the bird about the best position among the particles i.e. interaction inside the swarm. At each iteration the particle move towards optimum solution, through its present velocity, personal best solution obtained by themselves and global best solution obtained by all the particles until they find the food (optimal solution).

In an n-dimensional search space, position and velocity of particle j are represented by vectors $X_{ij} = (X_{i1}, X_{i2} \ldots X_{ip})$ and $V_{ij} = (V_{i1}, V_{i2} \ldots V_{ip})$ respectively. Let Xpbest vector and Xgbest be the personal and global best positions of the particles for i^{th} variable. The generations are the independent variables of the problem. The modified velocity and position of each particle can be calculated using current velocity and distance from Xpbest and Xgbest as follows:

$$V_{ij}^{k} = V_{ij}^{k-1} + C_1 * r_1 * \left(Xpbest_{ij}^{k-1} - X_{ij}^{k-1} \right) + C_2 * r_2 * \left(Xgbest_{i}^{k-1} - X_{ij}^{k-1} \right)$$

i=1, 2 … NG, j=1, 2 … p (3.1a)

Position update equation is given by

$$X_{ij}^{k} = X_{ij}^{k-1} + V_{ij}^{k}$$

i=1, 2 … NG, j=1, 2 … p (3.1b)

where

k	Iteration count.
V_{ij}^{k}	Value of velocity of jth particle (of ith generator) at kth iteration.
X_{ij}^{k}	Value of position of j^{th} particle (of i^{th} generator) at k^{th} iteration.
C_1, C_2	Acceleration coefficients.
$Xpbest_{ij}^{k}$	Value of personal best position of j^{th} particle (for i^{th} generator) in k^{th} iteration.
$Xgbest_{i}^{k}$	Value of best position of swarm (for i^{th} generator) in k^{th} iteration.
NG	No. of Generating buses.
p	No. of particles in the swarm.
r_1, r_2	Two separately generated random numbers from the uniformly distributed range of (0, 1).

Velocities are updated by the equation (3.1a) and the positions of each particle for each decision variable are calculated by equation (3.1b) [26].
To increase the convergence rate of the PSO algorithm the inertia weight is proposed in the velocity equation [38, 39]. By using the equation for the velocity with the inertia weight ‘W’, the suggested particle velocity will be changed to:

$$V_{ij}^{k} = W*V_{ij}^{k-1}+C_1 * r_1\left(Xpbest_{ij}-X_{ij}^{k-1}\right)+C_2 * r_2(Xgbest_{i}-X_{ij}^{k-1}) \quad i=1, 2 \ldots NG, j=1, 2 \ldots p \qquad (3.1c)$$

where: W is the inertia weight.

Because of this inertia weight some of the particles maintain their velocity from previous iteration to new iteration. In order to use the inertia weight in this paper, a descending linear function is used. There are other methods of using inertia weights. But, details of the same have not been investigated in the work reported in this dissertation. The best range for changing this function value for the convergence and obtaining the best possible solution is between 0.9 and 0.4 [26]. Due to the inertia weight used in velocity equation the swarm get enabled to fly in larger area of the search space (W = 0.9) and at the end of the iterations, the search space will be smaller (W = 0.4). Inertia weight increases the chance to obtain a best solution for an optimization problem. In general, a linear descending function for inertia weight equation is shown in the following equation [36-39].

$$W = W_{max}-k*(W_{max}-W_{min})/iter_{max} \qquad (3.1d)$$

Where:

W	inertia weight factor
W_{max}	maximum value of velocity weighting factor
W_{min}	minimum value of velocity weighting factor
$iter_{max}$	maximum number of iteration
k	current number of iteration

4.2 PARTICLE SWARM OPTIMIZATION (PSO) AND TRADITIONAL SEARCH METHODS

A comparison between Conventional Optimization Techniques and evolutionary algorithms (like GA and PSO) is presented in Table 3.1 below [40, 41].

Unlike other random search algorithms, each potential solution (called a particle) is also assigned a randomized velocity and then flown through the problem hyperspace.

The most striking difference between PSO and the other evolutionary soft computing algorithms is that PSO chooses the path of cooperation over competition. Where the other algorithms commonly use some form of decimation such as survival of the fittest. The PSO population is stable and individuals are not destroyed or created. The particles are influenced by the best performance of their neighbors. The particles eventually converge on optimal points in the problem domain.

The PSO traditionally does not have any genetic operators like crossover between individuals and mutation. Also, other individuals never substitute particles during the run. The PSO refines its search by attracting the particles to positions with good solutions.

Particles update themselves with the internal velocity.

They also have memory, in terms of pbest and gbest which is important to the algorithm.

Compared with GAs, the information sharing mechanism in PSO is significantly different. The chromosomes share information with each other in GA. Thus, the whole population moves like a one group toward an optimal area. In PSO, only gbest and pbest gives out the information. It is a one-way information sharing mechanism. Here, the evolution only looks for the best solution.

Compared to the GA, the advantage of PSO is that it is easy to implement and there are few parameters to adjust.

Table 4.1: Comparison between Conventional Optimization Procedures and Evolutionary Algorithms

Property	Evolutionary	Traditional
Search space	Population of potential solutions	Trajectory by a single point
Motivation	Natural selection and Social adaptation	Mathematical properties (gradient, Hessian)
Applicability	Domain independent, Applicable to variety of problems	Applicable to a specific problem domain
Transition	Probabilistic	Deterministic
Prerequisites	An objective function to be optimized	Auxiliary knowledge such as gradient vectors
Initial guess	Automatically generated by the algorithm	Provided by user
Flow of control	Mainly parallel	Mainly serial
CPU time	Large	Small
Results	Global optimum more probable	Local optimum, dependant of initial guess
Advantages	Global search	Convergence proof
Drawbacks	No general formal convergence proof	Locality, computational cost

4.3 BIOLOGICAL TERMINOLOGY:

Particle Swarm Optimization (PSO) is a biologically inspired computational search and optimization method developed by Eberhart and Kennedy in 1995 based on the social behaviors of birds flocking and fish schooling.

Swarm: An apparently disorganized population of moving particles is known as swarm that tend to cluster together towards a common optimum while each particle seems to be moving in a random direction.

Particle (X): It is a candidate solution, in an i-dimensional space. At time t, the j^{th} particle $X_j(t)$ can be described as X_j $(t)=[X_{1j}(t),X_{2j}(t),\ldots,X_{ij}(t)]$, where X_{ij} are the optimized parameters and $X_{ij}(t)$ is the position of the j^{th} particle with respect to the i^{th} dimension; i.e. the value of the i^{th} optimized parameter in the j^{th} candidate solution.

Velocity (V): It is the velocity of a moving particle, can be represented by an i-dimensional vector, where i is the number of optimized parameters. At time t, the j^{th} particle $V_j(t)$ can be described as V_j $(t)=[V_{ij}(t),V_{2j}(t),\ldots,V_{ij}(t)]$.

Personal best (Pbest): The personal best position associated with j^{th} particle is the best position that the particle has visited yielding the highest fitness value for that particle.

Global best (Gbest): The best position associated with j^{th} particle that any particle in the swarm has visited yielding the highest fitness value for that particle. This represents the best fitness of all the particles of a swarm at any point of time.

The optimization process uses a number of particles constituting a swarm that moves around a pre-defined search space looking for the best solution. All the particles are treated as a point in the D-dimensional space in which the particle adjusts its "flying" according to its own flying experience as well as the flying experience of other neighboring particles of the swarm. Each particle keeps track of its coordinates in the pre-defined space which are associated with the best solution (fitness) that it has achieved so far and this value is called pbest. The best value that is tracked by the PSO so far is the best value obtained by any particle in the whole swarm and is called gbest. The velocity of each particle is changed toward its pbest and the gbest position at the end of iteration. Each particle tries to modify its current position and velocity according to the distance between its current position and pbest and the distance between its current position and gbest [42].

4.4 COMPUTATIONAL PROCEDURE:

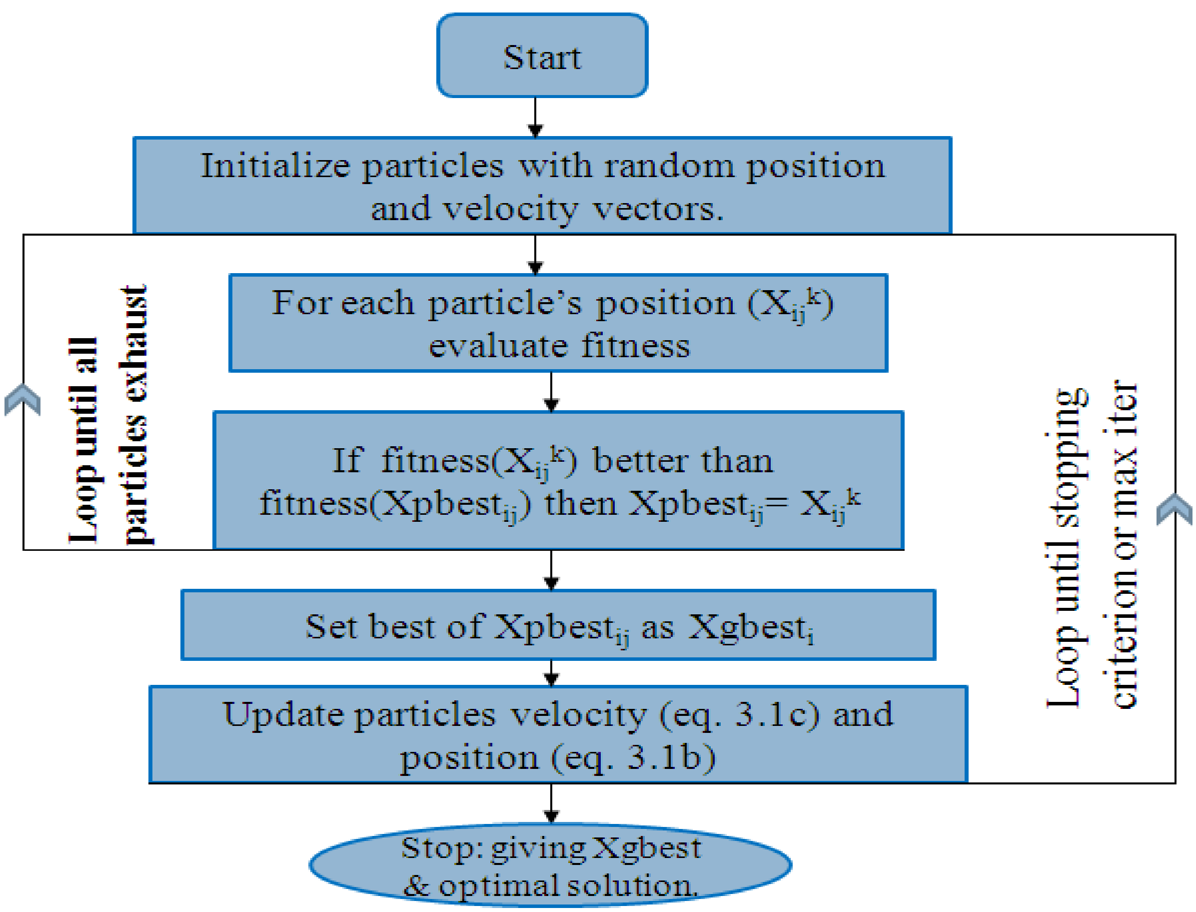

Fig 4.1: Generalized Flowchart for Particle Swarm Optimization Algorithm

The general computational procedure for the Particle Swarm Optimization is as follows:

1. Before the iteration starts, initialize the particles with random position and velocity vectors.
2. For each of the particle's position (X_{ij}^{k}) calculate the value of the objective function (F; we also call it fitness function).
3. If $F(X_{ij}^{k})$ is less than $F(Xpbest_{ij})$, then assign the value of $Xpbest_{ij}$ as X_{i}^{k} (do it for all the particles).
4. Determine the best value of $Xpbest_{ij}$ considering its fitness value. If F(best of $Xpbest_{ij}$) is less than $F(Xgbest_{i})$, than assign the value of best of $Xpbest_{ij}$ to the $Xgbest_{i}$.
5. Calculate the new velocity vector using equation (3.1c) and the new position vector using equation (3.1b).
6. Iterates the loop until either the stopping criteria met or the max iteration is achieved.
7. After iteration completes, give $Xgbest_{i}$ as the optimal solution and the fitness corresponding to it as the optimum value.

4.5 ADVANTAGES AND LIMITATIONS OF PARTICLE SWARM OPTIMIZATION

A PSO is one of the most powerful methods for resolving the non-smooth global optimization problems and has many key advantages as follows:

I. PSO is a derivative-free technique similar to other heuristic optimization techniques.
II. This algorithm is easy in its concept and coding implementation compared to other heuristic optimization techniques.
III. This algorithm is less sensitive to the nature of the objective function compared to the conventional mathematical approaches and other heuristic methods.
IV. This algorithm has limited number of parameters including only inertia weight factor and two acceleration coefficients in comparison with other competing heuristic optimization methods. The impact of parameters to the solutions is considered to be less sensitive compared to other heuristic algorithms [41].
V. This algorithm seems to be somewhat less dependent on a set of initial points compared to other evolutionary methods, implying that convergence algorithm is robust.
VI. This techniques can generate high-quality solutions within shorter calculation time and stable convergence characteristics than other stochastic methods [43].

The major drawback of PSO, like in other heuristic optimization techniques, is that it lacks somewhat a solid mathematical foundation for analysis to be overcome in the future development of relevant theories. However, it is believed that the PSO-based approach can be applied in the off-line real-world load flow problems. Also, the PSO-based approach is believed that it has less negative impact on the solutions than other heuristic-based approaches. However, it still has the problems of dependency on initial points and parameters, the difficulty in finding their optimal design parameters, also the stochastic characteristic of the final outputs.

Chapter 5

SOLUTION OF MATHEMATICAL BENCHMARK FUNCTIONS USING PSO:

5.1 STEPS OF PARTICLE SWARM OPTIMIZATION IN MATLAB:

The basic steps for solving the optimization problem using Particle Swarm Optimization is same as explained in previous chapter. But with some modification we can use it for any type of objective function. Here PSO has been used for optimizing some mathematical functions, which are:

1. Rosenbrock's function: $100*(X_2^2-X_1)^2+(X_1-1)^2$
2. Beale function: $(1.5–X_1+X1*X2)^2 + (2.25–X_1+X1*X22)^2 + (2.625–X_1+X_1*X_2^3)^2$
3. Sphere function: $X_1^2 + X_2^2 + X_3^2$
4. Booth's Function: $(X_1+2*X_2-7)^2 + (2*X_1+X_2-5)^2$

The steps for optimizing any mathematical benchmark test function:

a. Initialize all the variable matrices using the '`zeros`' command of MATLAB.
b. Set the values of random numbers 'rp' and 'rg' assigned to personal and global best expressions respectively.
c. Set the values of acceleration constants '`cp`' and '`cg`' assigned to personal and global best expressions respectively and set the tolerance value.
d. Generate the random values of particles for both the X_1 and X_2 variables, also generate random velocity vectors V_1 & V_2 respectively.
e. Calculate the fitness for the assumed values of the positions of the particles.
f. Using the above fitness, Xpbest vector for both the variables X_1 and X_2 and Xgbest value is deduced.
g. Using the previous iteration values of personal best, global best and velocity vector, new velocity vector is generated in the current iteration using eq. (3.1a).
h. Using the new velocity vector and the old position vector a new position vector is generated for both the variables using eq. (3.1b).
i. Calculate fitness is using the new position vectors in the current iteration.
j. Using the new fitness values, the personal and global best values are updated.

k. The difference between the previous and the current fitness is calculated and checked against the tolerance value, if within the tolerance iteration stops and global best value is the solution else iteration flow goes back to step g.

In this way optimized value of objective function and the corresponding variable values are found.

5.2 DIFFERENT PARAMETERS OF PARTICLE SWARM OPTIMIZATION:

The various parameters of Particle Swarm Optimization are

1. No. of particles in the swarm, p.
2. Max. no. of iteration, it.
3. Random no. for personal & global factors rp & rg.
4. Acceleration constant for the personal and global factors, cp & cg.
5. Tolerance value, T.

The values of these parameters for optimizing various mathematical benchmark functions were chosen as:

1. p = to be fixed by user in run time.
2. it = 1000
3. rp=0.4 & rg=0.5.
4. cp=2 & cg=2.
5. T = 10^(-6).

5.3 APPLICATION OF PARTICLE SWARM OPTIMIZATION TO MATHEMATICAL BENCHMARK TEST FUNCTIONS:

Test functions, known as **artificial landscapes**, are useful to evaluate characteristics of optimization algorithms. In this case of application of Particle Swarm Optimization to the mathematical benchmark functions, the PSO algorithm can be applied directly to the particular mathematical function, i.e. without any modification. As the mathematical functions are single objective functions and no equality criteria on the fitness function values, no further formulation for objective function is required and the inequality constraints on the variables, if present, are taken care of in the PSO algorithm itself.

The various benchmark test function optimized are as follows:

1. Rosenbrock Function:

$$f(x_1, x_2) = 100\ (x_2 - x_1^2)^2 + (x_1 - 1)^2$$

2. Beale's Function:

$$f(x_1, x_2) = (1.5 - x_1 + x_1x_2)^2 + \ (2.25 - x_1 + x_1x_2^2)^2 + \ (2.625 - x_1 + x_1x_2^3)^2$$

3. Sphere Function:

$$f(x_1, x_2, x_3) = \ x_1^2 + x_2^2 + x_3^2$$

4. Booth's Function:

$$f(x, y) = (x + 2y - 7)^2 + (2x + y - 5)^2$$

A general form of the equation, a plot of the objective function, constraints of the objective functions and the coordinates of global minima actual and with PSO are given herein. The effect of particle size is studied on various mathematical functions.

5.4 COMPUTATIONAL RESULTS:

1. Rosenbrock's Function:

$$f(\boldsymbol{x}) = \sum_{i=1}^{n-1} \left[100\left(x_{i+1} - x_i^2\right)^2 + (x_i - 1)^2\right].$$

The minimum values for the Rosenbrock's function are as shown below:

$$\text{Minimum} = \begin{cases} n = 2 & \rightarrow \quad f(1,1) = 0, \\ n = 3 & \rightarrow \quad f(1,1,1) = 0, \\ n > 3 & \rightarrow \quad f\left(-1, \underbrace{1, \ldots, 1}_{(n-1)\text{ times}}\right) = 0. \end{cases}$$

for $-\infty \leq x_i \leq \infty$, $1 \leq i \leq n$

Here Rosenbrock function with n=2 has been considered i.e.

$$f(x_1, x_2) = 100\,(x_2 - x_1^2)^2 + (x_1 - 1)^2$$

Detail discussion to optimize Rosenbrock function with PSO is given below:

1. Generate the random Position vectors for the two variables, i.e. X_1 {} and X_2 {}.
2. Generate the random Velocity vectors for the two variables, i.e. V_1 {} and V_2 {}. (No. of elements in the vectors is equal to no. of particles i.e. 'P')
3. So at 0^{th} iteration

Random velocities generated by MATLAB		Random positions generated by MATLAB		Function values at random positions
V_{1j}^0	V_{2j}^0	X_{1j}^0	X_{2j}^0	f^0
0.3111	0.5949	1.2886	0.4155	155.1104
0.9234	0.2622	**0.7572**	**0.6025**	**0.1437**
0.4302	0.6028	1.6232	0.9418	286.9471
0.1848	0.7112	1.0657	0.4610	45.5177
0.9049	0.2217	0.7015	1.6886	143.2694
0.9797	0.1174	1.8780	0.3895	985.0782
0.4389	0.2967	1.7519	0.4518	685.5702
0.1111	0.3188	1.1003	0.3414	75.5734
0.2581	0.4242	1.2450	0.4553	119.8689
0.4087	0.5079	1.1741	0.8714	25.7442

4. Personal best values for each particle will be their own position in the first iteration.

$$Xpbest_1 = X_1^0 \text{ and } Xpbest_2 = X_2^0$$

5. Global best value of position will be positions of that particle, corresponding to which function value is minimum.

$$Xgbest_1 = 0.7572 \text{ and } Xgbest_2 = 0.6025$$

6. Now new velocity vectors can be determined for both the variables, i.e. $\begin{bmatrix} V_{1j}^{k+1} \\ V_{2j}^{k+1} \end{bmatrix}$ for all the particles using eq. (3.1c)
7. Than new position vectors, i.e. $\begin{bmatrix} X_{1j}^{k+1} \\ X_{2j}^{k+1} \end{bmatrix}$ for all the particles using eq. (3.1b).

8. Again the objective function value is calculated using the new position vectors of the two variables for all the particles.
9. At 1st iteration

The newly calculated velocity vectors

V_{1j}^{1}	V_{2j}^{1}
-0.2516	0.7221
0.8306	0.2359
-0.4790	0.2029
-0.1422	0.7813
0.8697	-0.8867
-0.2395	0.3186
-0.5999	0.4175
-0.2431	0.5478
-0.2556	0.5287
-0.0492	0.1879

The newly calculated positions of particles

X_{1j}^{1}	X_{2j}^{1}
1.0371	1.1376
1.5878	0.8384
1.1442	1.1448
0.9235	1.2422
1.5712	0.8020
1.6385	0.7081
1.1520	0.8694
0.8572	0.8892
0.9893	**0.9840**
1.1249	1.0593

Function values for positions

f^{1}
0.3872
283.5112
2.7242
15.1731
278.0776
391.0947
20.9730
2.4072
0.0028
4.2594

10. Global best value of position will be changed to positions of that particle, corresponding to which function value is now minimum as compared to the last Global best value .

$$\begin{bmatrix} Xgbest_1 \\ Xgbest_2 \end{bmatrix} = \begin{bmatrix} 0.9893 \\ 0.9840 \end{bmatrix}$$

11. New personal best values are decided by comparing the last two iteration's function values.

0^{th} iteration positions				
Random Positions		Fitness Values	Personal Best	
X_1^0	X_2^0	f^0	X_{Pbest1}	X_{Pbest2}
1.2886	0.4155	155.1104	1.2886	0.4155
0.7572	0.6025	0.1437	0.7572	0.6025
1.6232	0.9418	286.9471	1.6232	0.9418
1.0657	0.4610	45.5177	1.0657	0.4610
0.7015	1.6886	143.2694	0.7015	1.6886
1.8780	0.3895	985.0782	1.8780	0.3895
1.7519	0.4518	685.5702	1.7519	0.4518
1.1003	0.3414	75.5734	1.1003	0.3414
1.2450	0.4553	119.8689	1.2450	0.4553
1.1741	0.8714	25.7442	1.1741	0.8714

1^{st} iteration positions				
New Positions		Fitness Values	Personal Best	
X_1^1	X_2^1	f^1	X_{Pbest1}	X_{Pbest2}
1.0371	1.1376	0.3872	**1.0371**	**1.1376**
1.5878	0.8384	283.5112	0.7572	0.6025
1.1442	1.1448	2.7242	**1.1442**	**1.1448**
0.9235	1.2422	15.1731	**0.9235**	**1.2422**
1.5712	0.8020	278.0776	0.7015	1.6886
1.6385	0.7081	391.0947	**1.6385**	**0.7081**
1.1520	0.8694	20.9730	**1.1520**	**0.8694**
0.8572	0.8892	2.4072	**0.8572**	**0.8892**
0.9893	0.9840	0.0028	**0.9893**	**0.9840**
1.1249	1.0593	4.2594	**1.1249**	**1.0593**

Bold figures are the updated values of X_{Pbest1} and X_{Pbest2} , on the basis of comparison between the fitness value.

12. Check if the difference in function values between two consecutive iterations is less than a prescribed value. If not, repeat the procedure.

With Particle Swarm Optimization, the minimum values of the Rosenbrock function are:

Table 5.1: Result for Rosenbrock's Function

No. of particles	No. of iterations	x_1	x_2	$f(x_1,x_2)$
10	112	1.0006	1.0006	$4.782*10^{-7}$
20	130	1.0067	1.0136	$4.5792*10^{-5}$
30	154	1.0000	1.0000	$4.3841*10^{-11}$
40	172	1.0000	1.0000	$1.0951*10^{-17}$

Table 5.1 shows the results of Rosenbrock function. It is observed that as the no. of particles is increased the no. of iterations increase and the optimum value are obtained with greater accuracy.

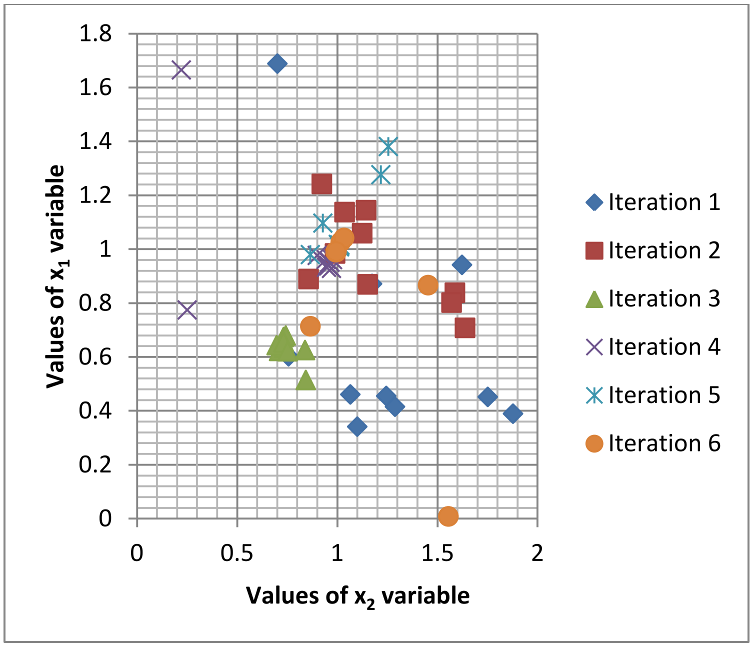

Fig 5.1(a): Mapping Of 10 Particle Position Values for 6 Iterations for Rosenbrock's Function

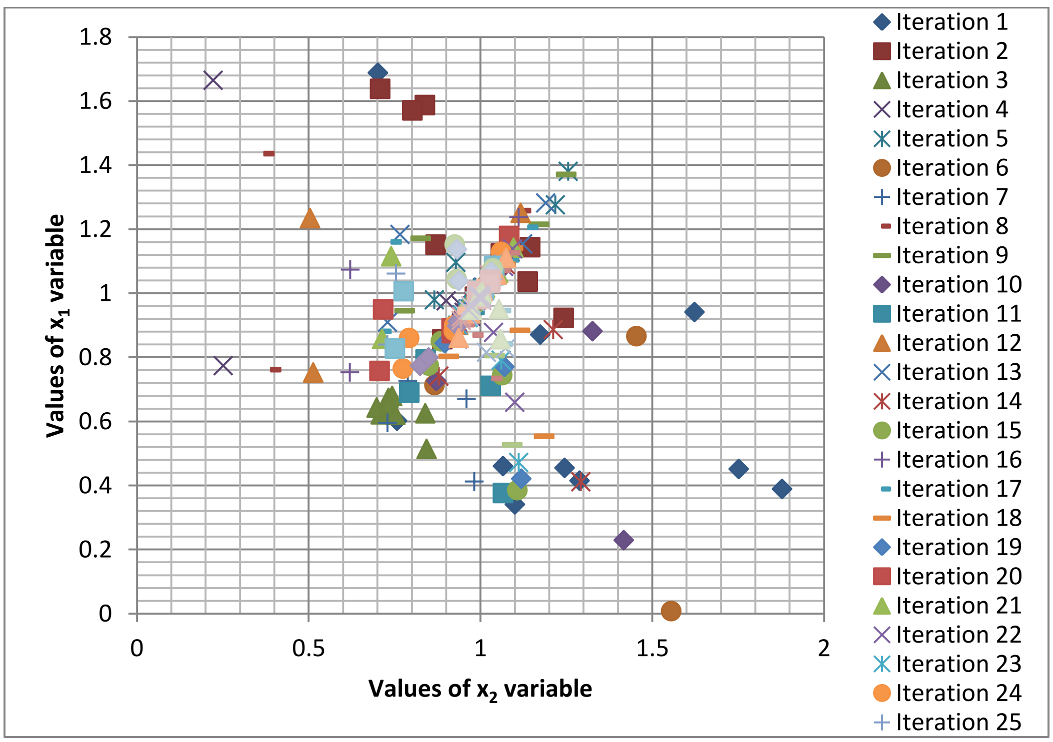

Fig 5.1(b): Mapping Of 10 Particle Position Values for 25 Iterations for Rosenbrock's Function

As we can see from the fig 5.1(a) and fig 5.1(b), that as the iteration count increases the particles start converging at the (1, 1) and oscillates about it until value of all the particles converges to optimum value i.e. (1, 1) for each particle.

Chapter 6

OPTIMAL PLACEMENT OF SVC

6.1 PROBLEM FORMULATION:

In its simplest form, the SVC consists of a thyristor-controlled reactor in parallel with a bank of capacitors. As for as operation is concern, the SVC behaves like a shunt connected Variable reactance. It either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the power network. It is used extensively to provide fast reactive power and voltage regulation support. The thyristor's firing angle control enables the SVC to have almost instantaneous speed in response. As an important component for voltage control, it is usually installed at the receiving node of the transmission lines. The SVC is modeled as a shunt element with a compensated reactive power, Q_{SVC}, set by available inductive and capacitive susceptances.

The current drawn and reactive power injected by the SVC can be expressed as:

$I_{svc} = j B_{svc} *V$

$Q_{svc} = -jB_{svc}*V^2$

$B_{svc(min)} \leq B_{svc} \leq B_{svc(max)}$

Where B_{SVC}, I_{SVC} and Q_{SVC} are the susceptance, injected current and injected reactive power of SVC, respectively.

6.2 OBJECTIVE FUNCTION:

A multi-objective function is considered in searching for a solution consisting of both the SVC location and size that minimizes the voltage deviation, active power loss and installation cost described as follows:

6.2.1 MINIMIZATION OF VOLTAGE DEVIATION:

The voltage improvement index for a power system is defined as the deviation of voltage magnitudes at each from unity. Thus, for a given system, the voltage improvement index is defined as,

$$L_v = \sum_{i=1}^{n} \left\{ \frac{V_{iref} - Vi}{V_{iref}} \right\}$$

Here: n is the number of buses, V_{iref} is the reference voltage at bus i and V_i is the actual voltage at bus i.

6.2.2 MINIMIZATION OF INSTALLATION COST:

The total SVC cost in USD/KVar is given as :

C_{svc} = $0.0003*S^2 - 0.3051*S + 127.38$ [USD/KVar] … 5.6

Where:

C_{svc} is the cost of SVC devices in [USD/KVar]

S is Operating range of SVC in [MVar]

The cost of installation of SVC devices is mathematically formulated and given by the following equation:

IC = C_{svc}*S*1000

Where:

IC=the installation cost of SVC device in [USD]

6.3 OPERATIONAL CONSTRAINTS:

The objective of applying SVC is to control system Variables such as bus voltages, thus the following constraints are considered:

Bus voltage limits:

Bus voltages should be maintained around the nominal value and it is given by:

$V_{i(min)} \leq V_i \leq V_{i(max)}$

The acceptable deviations can reach up to 10% of the nominal values.

6.4 FITNESS FUNCTION:

The main objective of this paper is finding the optimal location of SVC in such way that the total the cost of installation are minimized and at the same time system constrains are met. In this condition, the voltage at different buses is kept within acceptable levels.

The fitness function of this problem according to the above mentioned statement is as follow:

FF = W1*IC + W_2*V_k

Where:

W_1 and W_2 are the weight factors.

IC is cost of installation of SVC

V_k is voltage contribution at bus K.

6.5 AN ALGORITHM FOR OPTIMAL PLACEMENT AND SIZING OF SVC USING PSO IS GIVEN BELOW:

6.5.1 OVERVIEW OF PARTICLE SWARM OPTIMIZATION ALGORITHM:

1. Generate the particles: $X_{gi} = X_1, X_2,\ldots, X_n$
2. Generate the velocity Vi.
3. Evaluate the fitness function.
4. Evaluate pbest value and then identify gbest value.
5. Update the velocities (using equation (4.7)).
6. Update generation (using equation (4.8)).

6.5.2 IMPLEMENTATION OF PROPOSED ALGORITHM:

Step1: Enter line data and bus data

Step2: Set the loading

Step3: Run the load flow and determine voltage for all the buses.

Step4: Identify the weak buses for placement of SVC using voltage nominal value.

Step6: Generate randomly 'n' number of particles, where each particles represents as particle[i] = [b_{svc1}, b_{svc2}………..$b_{svc\ n}$] .

Step7: Generate the particle velocity $V[i] = 0.4*rand*V_{max}$

Step8: Run the load flows by placing a particle 'i' at the weak bus for reactive power compensation and store the voltage.

Step9: If the range of voltages lie in the range of $.95pu<v<1.05pu$ then go to next step else goto step13.

Step10: Evaluate the fitness function.

Step11: Determine pbest value and then identify gbest value.

Step12: Update the velocities and position of particle by using equations (4.7) & (4.8).

Step13: If maximum iteration number is reached , then go to next step else go to step6.

Step14: Evaluate transmission losses after svc is placed.

Step15: Stop

Result of sizing of SVC, voltage profile improvement, transmission losses reduction, at several loading condition shown in next Chapter.

Chapter 7

RESULT AND FUTURE SCOPE

7.1 RESULT:

This chapter presents the results obtained on the performance of power system with the placement of SVC. The installation of SVC, has been studied for their placement at optimal location decided by PSO. The performance has been studied on 14-bus systems. The data used for these case studies is given in Appendix-1.

The parameter of the optimization algorithm is identified through trial and error methods are listed below:

Table7.1: Parameter of Optimization Technique

PSO Parameter	Value
Population Size	150
Inertia Weight, w	.4 to .9
No. of Iteration	50

7.2 ANALYSIS OF 14-BUS SYSTEM:

The 14-bus system consist of 14 buses and 20 transmission line.

Table 7.2: Voltage and Angle of IEEE 14-BUS System

BUS No.	Without SVC			With SVC		
	Voltage	δ	MVAr	Voltage	δ	MVAr
1	1.06	0	0	1.06	0	0
2	1.045	-0.2097	0	1.045	-0.2091	0
3	1.01	-0.4695	0	1.01	-0.4684	0
4	0.908	-0.6855	0	1.031	-0.6422	0
5	0.97	-0.5538	0	1.017	-0.5347	0
6	1.07	-0.4182	0	1.012	-0.4165	0
7	0.97	-0.5538	0	1.017	-0.5427	0
8	1.09	-0.376	0	1.09	-0.3754	0
9	0.905	-0.6164	0	0.9914	-0.5976	0
10	0.8253	-0.8292	0	1.034	-0.7453	0
11	0.816	-0.8404	0	1.0014	-0.7462	.52
12	0.8789	-0.7155	0	0.9996	-0.6764	0
13	0.874	-0.7123	0	0.9904	-0.6735	0
14	0.8663	-0.699	0	0.9529	-0.6454	0

The result obtained with the algorithm has been compared to those calculated by power flow solution. Initially, the system was heavily loaded. Consequently, all the voltages of the load buses shown in table 7.2. Bus no. 4, 9, 10, 11, 12, 13, 14 out of range of limit, which is below 0.95 Pu. After installation of SVC with 52 MVAR at bus no. 11 the voltages of weak buses are increased as shown in table 7.2.

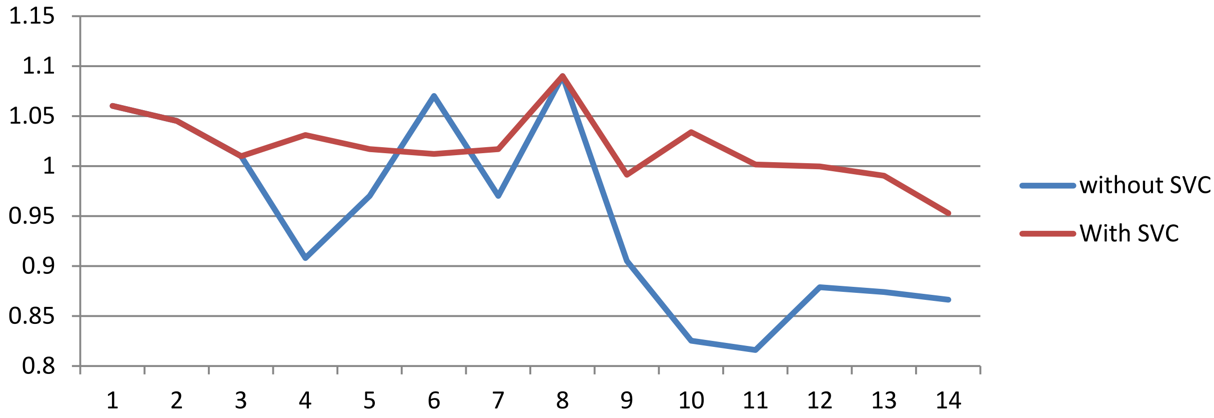

Fig 7.1: Voltage Profile in IEEE 14- Bus System.

With SVC placed at this bus the voltage profile at each bus is plotted in Figure 7.1. It is obvious that the bus voltage profile has been largely enhanced and the maximum deviation occurs at bus no.11.

7.3 FUTURE SCOPE:

Enough future scope is there to work in the area of PSO, a few aspects of possible future research work are given below:

a. Here one can work on the selection criteria of various constants in the PSO algorithm like acceleration constants (i.e. C_1 and C_2) and random no. (i.e. r_1 and r_2).
b. Computation of W- inertia factor.
c. Consideration of other objectives of Power Systems like environmental pollution, multiple valve point effects, security etc.

APPENDIX - I

I.1) IEEE 14 BUS SYSTEM:

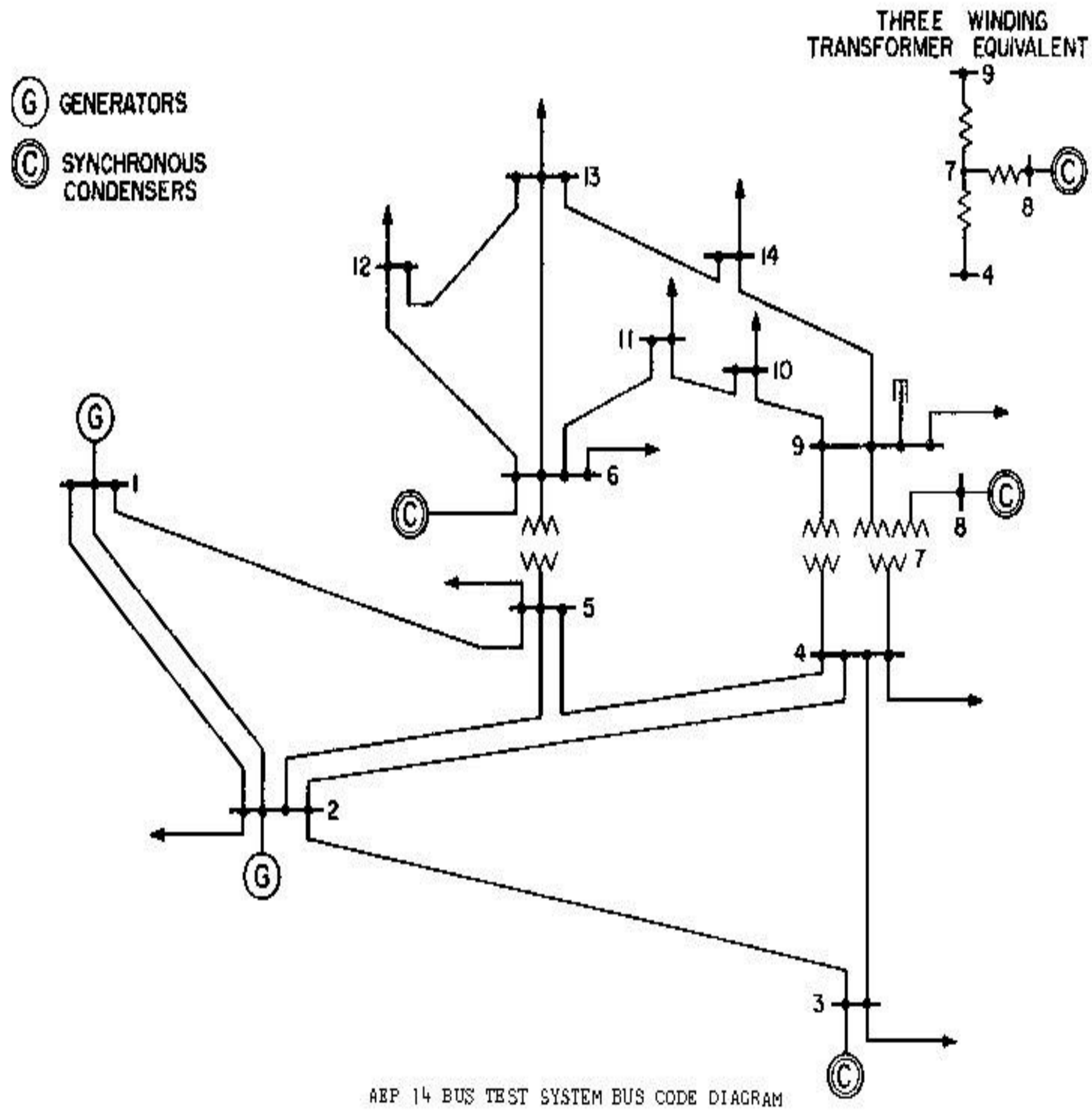

Fig. (I-A): BUS-CODE DIAGRAM 14 BUS SYSTEM

TABLE (I-A): IMPEDANCE AND LINE-CHARGING DATA (14 BUS SYSTEM)

Line Designation	Resistance p.u.*	Reactance p.u.*	Line Charging	Tap Setting
1-2	0.01938	0.05917	0.0264	1
1-5	0.05403	0.22304	0.0246	1
2-3	0.04699	0.19797	0.0219	1
2-4	0.05811	0.17632	0.0187	1
2-5	0.05695	0.17388	0.0170	1
3-4	0.06701	0.17103	0.0173	1
4-5	0.01335	0.04211	0.0064	1
4-7	0	0.20912	0	1
4-9	0	0.55618	0	1
5-6	0	0.25202	0	1
6-11	0.09498	0.19890	0	1
6-12	0.12291	0.25581	0	1
6-13	0.06615	0.13027	0	1
7-8	0	0.17615	0	1
7-9	0	0.11001	0	1
9-10	0.03181	0.08450	0	1
9-14	0.12711	0.27038	0	1
10-11	0.08205	0.19207	0	1
12-13	0.22092	0.19988	0	1
13-14	0.17093	0.34802	0	1

* Impedance and line-charging susceptance in p.u. on a 100 MVA base. Line charging one-half of the total charging of line.

TABLE (I-B): BUS DATA OR OPERATING CONDITIONS (14 BUS SYSTEM)

Bus No.	Voltage		Generation	Generation	Load	Load
	Magnitude (p.u.)	Phase Angle (deg.)	MW	MVAR	MW	MVAR
1*	1.06	0	0	0	0	0
2	1	0	40	0	21.7	12.7
3	1	0	0	0	94.2	19.0
4	1	0	0	0	47.8	-3.9
5	1	0	0	0	7.6	1.6
6	1	0	0	0	11.2	7.5
7	1	0	0	0	0	0
8	1	0	0	0	0	0
9	1	0	0	0	29.5	16.6
10	1	0	0	0	9.0	5.8
11	1	0	0	0	3.5	1.8
12	1	0	0	0	6.1	1.6
13	1	0	0	0	13.5	5.8
14	1	0	0	0	14.9	5.0

* Slack Bus

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